Lecture Notes in Civil Engineering

Luís Bragança · Katerina Tsikaloudaki · Christina Giarma · Ricardo Mateus · Karolos Kontoleon · Rand Askar · Adriana Salles · Camila Cervantes *Editors*

ReShaping the Built Environment through Sustainability and Circularity

Proceedings of ReSBE 2026 International Conference - Volume 2

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Editors

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Preface

As Organisers of ReSBE 2026, we are honoured to present the Proceedings of the International Conference *ReShaping the Built Environment through Sustainability and Circularity*, held in Thessaloniki, Greece, from the 20th to the 23rd of October 2026.

Published in Open Access by Springer, these Proceedings reflect our commitment to making research and practical innovation at the intersection of sustainability, circularity, and the built environment widely available. By ensuring that the contributions can be consulted, cited and applied without restrictions, we hope to support informed decisions and accelerate positive change in the built environment and in society as a whole.

Society and governments require a more efficient, resilient, and regenerative built environment. Buildings and infrastructure shape patterns of resource use, energy demand, carbon emissions, social well-being, and economic development. In this context, the Circular Economy offers a vital framework for decoupling value creation from the consumption of finite resources by extending the service life of products and materials, enabling reuse and recovery, and promoting the valorisation of by-products and waste. Construction and the built environment have therefore become priority areas for policy, research, and professional practice, including within the European Commission's Circular Economy Action Plan. In parallel, the implementation of sustainability principles into the various scales of the built environment remains a primary goal of numerous policies and scientific efforts worldwide. ReSBE 2026 responds to this complex agenda by moving beyond incremental improvement and by advancing transformative approaches that drive systemic change across the design, construction, operation, and renewal of the built environment.

The conference was organised by the Laboratory of Building Construction and Building Physics of the School of Civil Engineering, Aristotle University of Thessaloniki, and the Department of Civil Engineering of the University of Minho, in collaboration with the COST Action CA21103 "Implementation of Circular Economy in the Built Environment – CircularB", with the support of the International Initiative for a Sustainable Built Environment (iiSBE).

ReSBE 2026 also marked an important moment in the journey of COST Action CircularB. Alongside presenting cutting-edge research, the conference provided an opportunity to showcase the Action's achievements, disseminate its results, and celebrate the collective efforts of its international network in advancing circularity in the built environment. More importantly, it created a platform for engaging the wider scientific, professional, and policy communities, fostering new collaborations and extending the impact of CircularB beyond the lifetime of the Action.

Within the ReSBE 2026 programme, the 1SBE event "Sustainability in the Built Environment Supported by Circular Strategies: Theory Meets Practice" further strengthened the conference's international scope. As part of the SBE Conference Series, this event created a forum for dialogue among policymakers, industry representatives, social

partners, and academics, thereby linking scientific knowledge with implementation challenges and opportunities.

ReSBE 2026 was devoted to presenting recent scientific advances, showcasing practical applications that bridge academia and industry, and discussing key issues concerning the contribution of sustainability and circularity to the modern and future built environment, its construction, and its infrastructure. A principal goal of the conference was to foster the exchange of ideas, methods, and evidence in ways that inspired innovative research paths and advanced new collaborative endeavours across disciplines, geographies, and sectors.

The conference received 541 abstracts from 1368 authors across 71 countries. Following a rigorous peer-review process, 335 full scientific papers were accepted for publication and organised into twelve thematic sections:

1. *Circular Design and Construction:* design for adaptability, reuse, and disassembly; material passports; modularity and standardisation.
2. *Sustainable Buildings, Infrastructures and Cities:* sustainability assessment frameworks, sustainable design, construction, operation and management; synergies across scales.
3. *Lifecycle Assessment, Metrics and Monitoring:* whole-life carbon, embodied energy, circularity indicators, benchmarking frameworks, multi-criteria decision-support methods, and AI/IoT-enabled lifecycle monitoring.
4. *Digitalisation and Automation:* BIM-based approaches, digital twins, digital passports, AI-powered tools, and decision-support systems.
5. *Climate Adaptation and Resilience:* climate-responsive design, resilient infrastructure, and nature-based solutions.
6. *Energy and Performance:* net-zero energy, carbon-neutral buildings, renewable energy integration, and smart grids.
7. *Materials and Innovation:* bio-based and regenerative materials, advanced composites, and secondary raw materials through industrial symbiosis.
8. *Urban and Regional Perspectives:* circular cities, heritage regeneration, and urban mining.
9. *Financing and Market Transformation:* circular business models, green financing, and innovative procurement strategies.
10. *Policy and Governance:* regulatory frameworks, certification systems, and leadership for circularity.
11. *Stakeholders and Collaboration Models:* roles, interactions, and governance mechanisms for systemic change.
12. *Societal and Educational Dimensions:* awareness, equity, skills, and capacity-building for sustainable transitions.

The contributions in these proceedings offer readers a broad and timely overview of the concepts, tools, technologies, policies, and case studies that are shaping the transition towards a sustainable and circular built environment. They address questions of direct relevance to researchers, designers, engineers, architects, policymakers, educators, and industry stakeholders, from whole-life performance and digitalisation to financing models, governance frameworks, stakeholder collaboration, and capacity-building.

Taken together, these contributions demonstrate that innovation, circularity, and sustainability are deeply interconnected. They also show that progress depends not only on technical solutions, but also on new forms of cooperation, new metrics for value and performance, and a shared willingness to rethink established practices. In light of this, the present Open Access publication aims to be a collection of high-quality research and serve as a catalyst for further inquiry, dialogue, collaboration and action.

We extend our deepest gratitude to all authors, the members of the Scientific Committee, the reviewers whose careful work upheld the excellence of the selected articles, and our publishing partners for their invaluable support. May these Proceedings inspire and facilitate the ongoing effort to engineer a sustainable, circular, and regenerative built environment for all.

The Organising Committee,

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Katerina Tsikaloudaki
Christina Giarma
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Climate Adaptation and Resilience: Climate-Responsive Design, Resilient Infrastructure, and Nature-Based Solutions

Surface Matters: A Comparative Analysis of Material and Geometry Effects on Urban Microclimate in Northern and Southern European Regions

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Abstract. Urban surfaces play a critical role in shaping pedestrian-level microclimates, particularly under intensifying climate pressures across Europe. This study investigates how material selection and urban geometry influence Mean Radiant Temperature (MRT) and Physiological Equivalent Temperature (PET) at midday (12:00) in two contrasting climates: Limassol (Mediterranean) and Luleå (subarctic). Using calibrated ENVI-met simulations, alternative materials—including concrete, wood, metal, glass, and vegetation—were applied to ground, roof, and façade components within open (Pavilion) and enclosed (Patio) typologies. Results indicate that ground surfaces exert the strongest influence on pedestrian thermal conditions. Reflective hardscapes substantially increased MRT, intensifying heat stress, particularly in courtyards. Vegetated ground and façade systems consistently reduced radiant exposure and produced measurable PET improvements. Roof interventions showed limited impact at street level. The findings demonstrate that effective climate-responsive design must prioritize coordinated ground and façade strategies, tailored to specific climatic contexts rather than relying on isolated material substitutions.

Keywords: Urban Microclimate · Vertical and Horizontal Surfaces · Sustainable Urban Design · ENVI-met Simulation · Climate-Responsive Materials

1 Introduction

Urbanization and climate change intensify Urban Heat Island (UHI) effects, cooling demand, and outdoor discomfort in European cities [1]. Urban form and materials shape these conditions [2], making surfaces climate-regulating elements [3]. Roofs, pavements, plazas, corridors, and façades are exposed areas whose radiative, thermal, and moisture properties shape heat exchange [4]. Material and vegetation changes improve performance, mitigate UHI, and support stormwater management [5]. Impervious, low-albedo surfaces and anthropogenic heat intensify overheating [6], while vegetation, reflectivity, cool materials, and vegetated roofs/façades mitigate heat through shading, evapotranspiration, and insulation [7]. Microclimate depends on geometry: courtyard geometry,

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orientation, street layout, porosity, and vegetation affect shading, airflow, comfort, and cooling demand [8]. Canyon reflectivity may increase radiant exposure [9]. However, excessive reflectivity in dense canyons may increase radiant exposure at pedestrian level [9]. Climatic diversity limits universal prescriptions: southern regions face prolonged overheating and northern cities emerging heat risks [10], with morphology mediating impacts [11]. Projections require region-specific adaptation, including greening and drainage [12]. Despite research on individual techniques, few integrate materials, positioning, and geometry cross-climatically. This study examines ground, roof, and façade interventions in Sweden and Cyprus to clarify surfaces' microclimatic contribution and guide retrofitting priorities.

2 Methodology

The analysis compares two climatically contrasting European cities: Limassol, Cyprus (Csa – hot-summer Mediterranean), and Luleå, Sweden (Dfc – subarctic). Simulations were configured for a clear summer solstice day, 21 June, with results evaluated at 12:00, corresponding to peak solar exposure.

Two idealized urban morphologies were modelled within identical 102 m × 66 m urban blocks. The Patio typology represents an enclosed courtyard block measuring 102 m × 66 m, with a building height of 9 m. The Pavilion typology represents an open layout composed of freestanding 12 m × 12 m built volumes, also 9 m high. The surrounding streets are 21 m wide, producing an urban canyon height-to-width ratio of 9/21. Each typology was assessed in North–South (NS), East–West (EW), and Courtyard (CY) positions to capture the influence of orientation and enclosure (see Fig. 1).

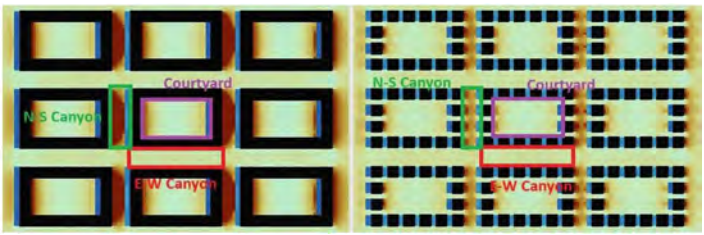


Fig. 1. The urban morphologies under investigation. The enclosed patio (left) and the open pavilion (right).

Material scenarios were applied to Ground, Roof, and Wall components, testing asphalt, concrete, wood, metal, glass, and vegetation according to surface applicability, as summarized in Table 1. Simulations were conducted in ENVI-met v5.7.2 using a 2 m grid. Mean Radiant Temperature (MRT) was extracted at pedestrian height (1.5 m), and PET was calculated to assess thermal comfort.

Table 1. Material Intervention Scenario Matrix.

Material Intervention	Ground (G)	Roof (R)	Wall (W)
Asphalt (A)	Baseline	Baseline	–
Concrete (C)	Tested	Tested	Baseline
Wood (W)	Tested	Tested	Tested
Metal (M)	–	Tested	Tested
Vegetation (V)	Tested	Tested	Tested
Glass (G)	–	–	Tested

3 Results

3.1 Influence of Ground Materiality on Microclimate at 12:00

The replacement of asphalt with concrete, wood, and vegetation was assessed at 12:00 in Limassol and Luleå, focusing on changes in Mean Radiant Temperature (ΔMRT) and their implications for outdoor thermal comfort across Pavilion and Patio typologies (NS, EW, CY). Results indicate that reflective hard surfaces primarily intensify radiant heat exposure at pedestrian level (1.5 m). In Limassol, concrete increased MRT by up to +13.9 °C in Courtyard configurations, while wood produced increases between +7.2 and + 10.2 °C. The higher reflectivity of these materials amplified shortwave radiation within enclosed geometries, strengthening radiant trapping effects. In contrast, vegetation consistently reduced MRT, with decreases ranging from −4.8 to −8.2 °C in Limassol and up to −5.1 °C in Luleå. Although absolute values were lower in the northern climate, the relative thermal behaviour of materials remained consistent across both case studies (see Fig. 2).

Geometric configuration further mediated outcomes. Patio typologies slightly moderated extreme radiant effects through partial self-shading. Overall, reflective hardscapes substantially increased radiant stress, whereas vegetation reduced radiant thermal loads and improved PET conditions.

At 12:00, replacing asphalt with concrete or wood increased PET in Limassol by + 1.5 to +2.5 °C in open streets and up to +5.5 °C in courtyards, intensifying heat stress. Similar trends appeared in Luleå, with PET increases of +3.0 to +5.0 °C. Vegetation reversed this pattern, reducing PET by up to −6.7 °C and markedly improving thermal comfort.

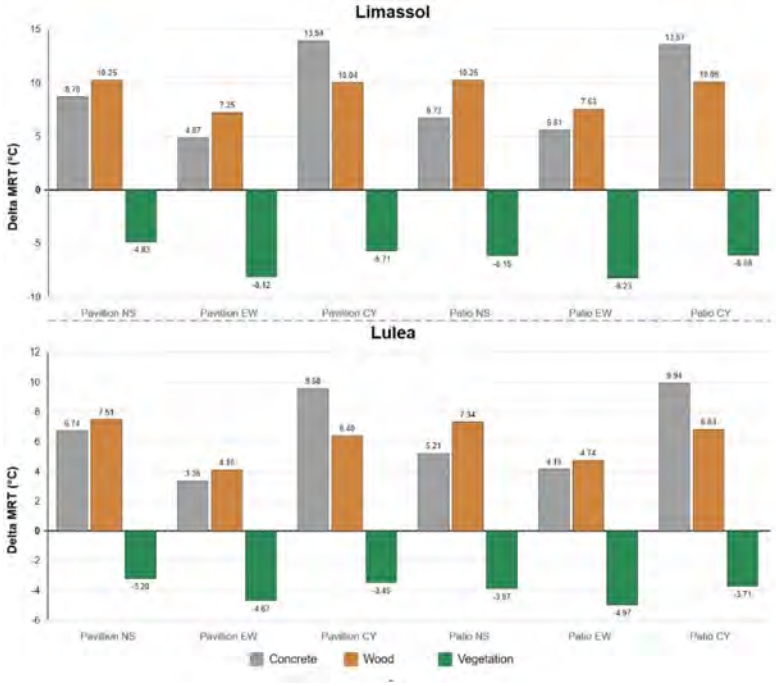


Fig. 2. Mean radiant temperature in Limassol (top) and Luleå (bottom), influenced by ground typology and materiality.

3.2 Influence of Roof Materiality on Microclimate at 12:00

Roof interventions influence pedestrian conditions indirectly, as their thermal effects must diffuse from the elevated plane down to 1.5 m through air mixing and canyon airflow. At 12:00, replacing an asphalt roof with alternative materials—concrete, wood, vegetation, and metal—in Limassol and Luleå produced markedly smaller microclimatic shifts than ground-level changes. Variations in Mean Radiant Temperature (ΔMRT) remained within approximately ±0.4 °C, indicating that roof materiality has a limited but measurable impact on pedestrian-level radiant conditions.

Metal and vegetated roofs demonstrated the most favourable performance. In Limassol, both produced slight MRT reductions of around −0.2 to −0.3 °C at midday. Metal limits heat gains through high reflectivity, whereas vegetation cools through evapotranspiration and reduced heat storage. Concrete yielded marginal improvements, while wood slightly increased MRT. Similar but smaller effects were observed in Luleå, confirming that roof-level interventions follow consistent material-related trends across both climatic contexts, although their influence remains weaker than that of ground modifications (see Fig. 3).

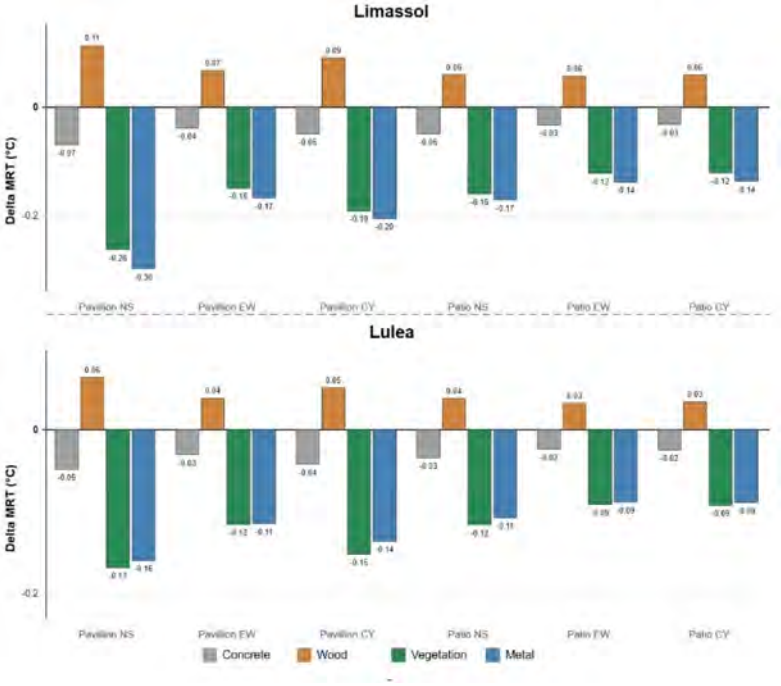


Fig. 3. Mean radiant temperature in Limassol (top) and Luleå (bottom), influenced by roof typology and materiality.

At 12:00, building geometry influenced how roof-level thermal effects reached pedestrian height. Across most materials, the open Pavilion typology produced slightly stronger changes in Mean Radiant Temperature (ΔMRT) at 1.5 m than the enclosed Patio. This suggests that open configurations facilitate vertical radiative and airflow exchange, allowing roof-generated thermal effects to interact more effectively with the pedestrian zone, whereas enclosed courtyards partially buffer this transfer.

However, PET results confirm that roof material changes exert minimal influence on overall thermal comfort. At midday in Limassol, switching from asphalt to metal reduced PET by only approximately 0.15 °C, a physiologically negligible improvement under extreme heat. Wood slightly worsened PET. Overall, roof strategies alone are insufficient without complementary ground-level interventions.

3.3 Influence of Wall Materiality on Microclimate at 12:00

Unlike roofs, façades form the immediate vertical enclosure of the pedestrian canyon and strongly influence solar reflection and heat exchange. Using concrete as the reference case, alternative wall materials—metal, glass, vegetation, and wood—were assessed at 12:00 in Limassol and Luleå. Highly reflective metal façades produced a thermodynamic trade-off: they significantly increased Mean Radiant Temperature (ΔMRT), with midday penalties in Limassol exceeding +4 °C and similarly high values in Luleå. This reflects

intense shortwave radiation back into the canyon, elevating radiant exposure at pedestrian level.

Vegetated façades demonstrated the most balanced performance, lowering MRT by up to −3.8 °C through shading and evapotranspiration. In contrast, wood cladding increased MRT, intensifying heat stress. Glass façades were associated with noticeable reductions in MRT, reaching up to −4.0 °C in some configurations, indicating lower longwave heat storage compared to massive concrete surfaces. Overall, façade materiality substantially affects pedestrian radiant conditions at midday (see Fig. 4).

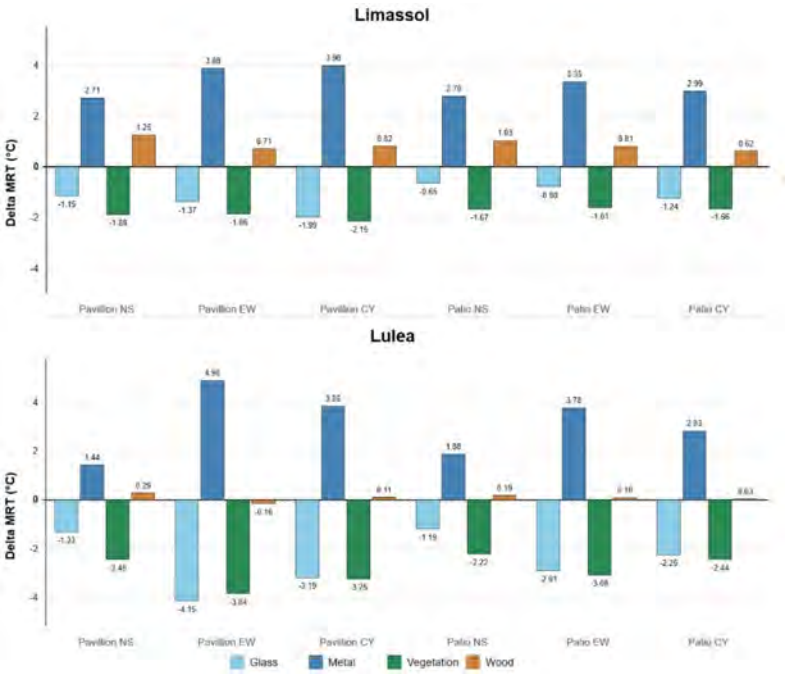


Fig. 4. Mean radiant temperature in Limassol (top) and Luleå (bottom), influenced by wall typology and materiality.

At 12:00, metal cladding increased radiant exposure, while wood also elevated radiant heat. In Limassol (NS Pavilion), replacing concrete with metal raised PET from 56.08 °C to 56.67 °C at midday; wood also intensified thermal stress. These results highlight how reflective or heat-retentive vertical materials amplify pedestrian discomfort.

Vegetated façades delivered the most consistent improvements. By combining shading and evapotranspiration, green walls reduced PET by approximately −0.6 to −1.0 °C in Limassol at 12:00, mitigating radiant heat exposure and improving comfort. Overall, façade treatments significantly shape lateral thermal exposure and can either offset or undermine ground-level cooling strategies.

4 Discussion and Conclusions

This study demonstrates that the microclimatic effect of material interventions depends on both material properties and surface position within the urban geometry. A clear hierarchy emerged: ground interventions had the strongest influence on pedestrian thermal comfort, façade treatments formed a secondary control layer, and roof interventions had limited impact at pedestrian level—reflecting the structure of radiative exchange within the urban canyon [13, 14]. Geometry further mediated performance, with patio configurations increasing radiant trapping risk and pavilion configurations increasing solar exposure, confirming that material substitutions cannot be evaluated independently from spatial configuration [15, 16]. MRT and PET proved more appropriate comfort indicators than surface properties alone [17]. The comparison between Limassol and Luleå showed consistent relative material behaviour across climates, while comfort implications differed according to baseline thermal stress, suggesting that physical mechanisms are transferable but design priorities must be adjusted to local climatic thresholds [18].

For retrofitting practice, the results support prioritising ground-level vegetation and targeted façade treatments over isolated roof strategies, and caution against treating reflective materials as universal mitigation tools. The study is limited to midday summer-solstice conditions; future work should extend analysis across full diurnal and seasonal cycles and integrate energy modelling with human response data.

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Tree Modelling Strategies for Outdoor Thermal Comfort Assessment in Complex Urban Contexts – A Case Study

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Abstract. Urban climate adaptation increasingly draws on nature-based strategies, with trees widely recognized for their role in moderating heat stress and shaping outdoor thermal comfort. Yet early-stage simulation workflows often treat trees as static shading, not accounting for their full dynamic climatic impacts. This study investigates how two different tree-modelling approaches in early design stages influence the environmental performance outcomes. Using Ladybug, which represents trees as fixed shade elements, and ENVI-met, which models them as biological systems, we compare courtyard and high-rise typologies in two climatic contexts – hot–humid Tel Aviv and hot–dry Jerusalem, under a constant floor area ratio (FAR) of 6. A summer design day is evaluated using the Universal Thermal Climate Index (UTCI), derived from air temperature, mean radiant temperature, humidity, and wind conditions. Results show that biological tree models produced higher UTCI values (indicating reduced thermal comfort) in most scenarios. In Jerusalem, ENVI-met UTCI values are about 10 °C higher than Ladybug due to vegetation-induced humidity and reduced wind flow, with deviation of air temperature (10–12%) and MRT (18–19%), indicating their strong influence on the microclimate. In Tel Aviv, both models show moderate heat stress with smaller differences, which may be attributed to high humidity. Here, relative humidity (6–8%) and wind speed (7–10%) show the least deviation. At 10:00, the courtyard shows higher UTCI than the high-rise due to restricted airflow. We argue for design processes that acknowledge trees as active climatic agents, enabling more informed and context-sensitive exploration of urban form under evolving climatic pressures.

Keywords: Urban Microclimate · Outdoor Thermal Comfort · Nature-Based Solutions · Environmental Performance

1 Introduction

Global climate change, driven by rapid population growth and accelerating urbanization, has intensified the Urban Heat Island (UHI) effect, with profound consequences for human health and biodiversity [1]. This phenomenon underscores the urgent need for

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effective adaptation strategies, particularly within the realm of urban design. While international mitigation policies seek to address the underlying causes of climate change, localised adaptation measures are indispensable for enabling cities to adjust to new environmental conditions.

Several studies highlight the importance of incorporating nature-based solutions (NbS) into urban environments to mitigate UHI. The cooling performance of NbS has been examined across various spatial scales, ranging from green walls [2], street trees [3] and urban parks and forests which influence the microclimate. Among these, street trees have been of great interest due to their direct impact on the pedestrian thermal comfort through the reduction of air temperature along with their dynamic shading ability. The microclimatic regulatory capacity of trees operates through three primary mechanisms: evapotranspiration, wind control, and shading [4]. Furthermore, the spatial configuration of trees and their proximity to built structures significantly affect their cooling potential and deliver better Outdoor Thermal Comfort (OTC) [5].

OTC is commonly evaluated using simplified thermal comfort indices. At the urban scale, Grasshopper plugins like Ladybug and Honeybee are widely used to compute OTC, primarily based on solar radiation and shading analyses [6]. In many modelling approaches, trees are represented as simplified mesh geometries [7] during the early design stages and OTC is assessed using radiation-based metrics while also accounting for wind flow and the influence of urban form on OTC [8]. These methods often neglect the physiological effects of the trees on the urban microclimate. This limitation highlights the need to better understand how tree characteristics and their biophysical processes interact with different building forms and influence outdoor thermal conditions. ENVI-met simulates trees as biophysical entities. However, it is computationally expensive and intensive.

This study asks how trees, when simulated as shading elements and as natural biophysical systems, impact OTC in an urban district and consequently early design decision-making. This also aligns with the idea of using trees as a low impact strategy that enhances environmental performance of the buildings while reducing reliance on energy-intensive urban interventions.

2 Methodology

The study examines the impact of trees on OTC in two climatic contexts—Tel Aviv and Jerusalem—by comparing ENVI-met and Ladybug simulation outputs. The analysis considers four variables (Fig. 1): (1) building Typology—courtyard and high-rise with a constant FAR of 6; (2) tree integration strategy—trees modelled as shading devices or as biological elements; (3) climatic context; and (4) a summer design day was derived from EPW data, defined as a statistically representative high-load condition based on peak temperature periods. While this enables controlled comparison, the use of a single day does not capture intra-seasonal variability. Trees were spaced at 8 m intervals, reflecting typical street-tree spacing observed in the study area and consistent with local urban planning guidelines [9]. As spacing influences shading, evapotranspiration, and airflow, results should be interpreted as specific to this configuration.

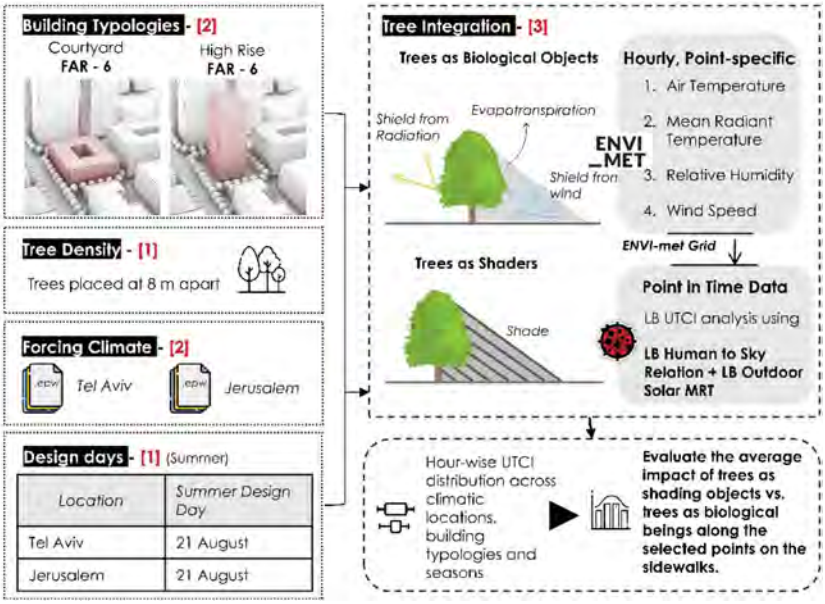


Fig. 1. Methodology Workflow

2.1 Analytical Workflow

ENVI-met v5.9.0, a validated microclimate model, in conjunction with the Morpho plugin for Grasshopper (Rhino 7), was used to simulate trees as biological entities. Trees as shading elements were simulated using Ladybug Tools v1.9.0 within the Rhino Grasshopper environment.

Since ENVI-met is a voxel-based, to reduce computational load, the surrounding building geometry was simplified. The grid resolution was defined as 3 m × 3 m × 3 m. The overall model dimensions were set to 50 voxels along the x-axis (150 m), 50 voxels along the y-axis (150 m), and 43 voxels along the z-axis. The materials were selected from the ENVI-met material library. The general configuration and parameters of the ENVI-met simulations are presented in Table 1.

Table 1. General settings for ENVI-met simulations.

Parameter	Value
Start Time and Date	20.08 | 12:00
Simulation Duration	36 h
Road Materiality	Legacy Asphalt Road
Sidewalks	Concrete Pavement Gray
Ground	Sandy Loam

Google Street View was used to identify the species present within the site. To represent the trees used widely by landscape architects - *Ficus macrocarpa and Ceratonia siliqua.* Based on their geometry and biophysical properties, these trees were defined as 'Spherical, small trunk, dense, medium (9 m) in the ENVI-met library (Albero) for representation in the model. In Rhino, the trees were modelled as a simple 3D shape to enable the radiation analysis. In both scenarios the trees are considered 9 m tall. Existing trees were excluded from the analysis, and new trees were placed at 8 m intervals along the sidewalks where analysis points are defined at 3 m interval (per voxel) and at pedestrian level of 1.5 m, as shown in Fig. 2.

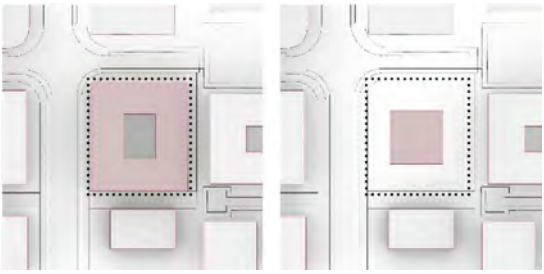


Fig. 2. Analysis points for data extraction; courtyard (left), high-rise (right)

2.2 Simulation Process

Air temperature, MRT, relative humidity and wind speed data were extracted from the ENVI-met outputs to calculate UTCI, for the hours between 9:00 a.m. and 6:00 p.m. on a representative summer day, capturing peak outdoor activity hours at a pedestrian level (1.5 m). The total number of simulation scenarios are presented in Table 2.

Table 2. Number of scenarios and simulations.

Variables	Name	
Typology	Courtyard, High-Rise	2
Seasons	Summer design day	1
Locations	Tel Aviv, Jerusalem	2
Tree Considerations	As Shaders, As Biological objects	2
	Total simulations for trees as shaders	4
	Total simulations for trees as biological objects	4
	Total simulations	**8**

2.3 Case Study

The selected test site is located in Holon (localized within Tel Aviv District) and is part of the current urban redevelopment initiative. The existing fabric consists of low-rise buildings ranging from two to seven stories with substantial tree coverage. The proposed plan replaces these with high-rise buildings, though at a moderate density relative to other urban centres.

2.4 Climatic Analysis

Both Tel Aviv and Jerusalem are classified as Hot Summer Mediterranean (Csa) climates under the Köppen–Geiger classification. Tel Aviv, which is located on the Mediterranean coast, experiences hot-humid summers and mild winters with consistently high relative humidity. Jerusalem, situated inland at a higher elevation than Tel Aviv, has hot- dry summers and cooler winters with precipitation (Fig. 3). Despite these differences, both cities receive similar levels of solar radiation because of their nearly identical latitude (~31.8°N). The wind rose diagram (Fig. 3) shows that both Tel Aviv and Jerusalem experience predominantly westerly to north-westerly winds, with most wind speeds ranging between 5–10 m/s on summer design day.

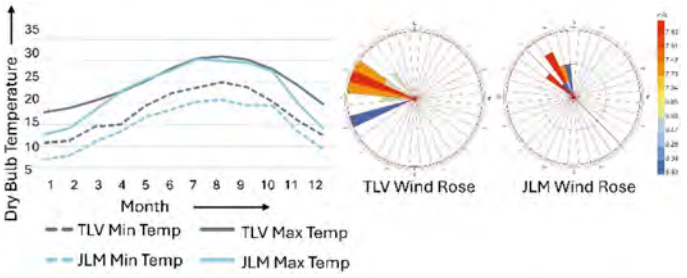


Fig. 3. Min and max Dry Bulb Temperatures for Tel Aviv and Jerusalem (Left), Wind Rose diagrams of Tel Aviv and Jerusalem (Right). Data derived from EPW weather files (EnergyPlus format), visualised via Climate.OneBuilding.org.

3 Results and Discussion

Following the simulations, UTCI values were calculated for each of the analysis points (Fig. 2) and then averaged to obtain a single representative value. This aggregation does not distinguish between under-canopy and exposed conditions, which may mask localised microclimatic variations. Figure 4 shows the LB and ENVI-met UTCI values in the Jerusalem climate for courtyard and high-rise typologies. It illustrates that the LB UTCI values range from 18–24 °C (no Thermal Stress as per UTCI classification) which are about 10 °C lower than the ENVI-met UTCI values ranging from 30–34 °C (Strong heat stress as per UTCI classification) across the typologies in Jerusalem. This difference in UTCI may be attributed to the additional humidity from the tree canopy

and the obstruction of wind flow which yielded higher UTCI values that were not taken into account in Ladybug Tools.

A sensitivity analysis (Fig. 5) was conducted using a relative percentage error (RPE) approach. A baseline UTCI was computed from EPW-derived climatic variables, after which each variable (air temperature, MRT, relative humidity, wind speed) was individually replaced with ENVI-met outputs while keeping the remaining inputs constant. The resulting deviation from the baseline was calculated as RPE = (UTCI_substituted − UTCI_baseline) / UTCI_baseline × 100, with hourly values (09:00–18:00) aggregated using the median. Results indicate that air temperature shows the least deviation (10% in courtyard, 12% in high-rise), followed by MRT (18% and 19%), suggesting these variables exert the strongest influence on local microclimatic conditions within the analysed design scenario.

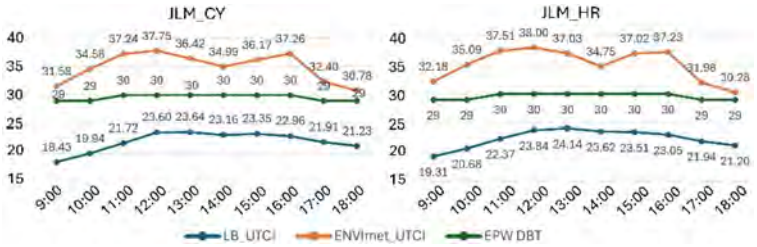


Fig. 4. Jerusalem UTCI results for Courtyard and High Rise

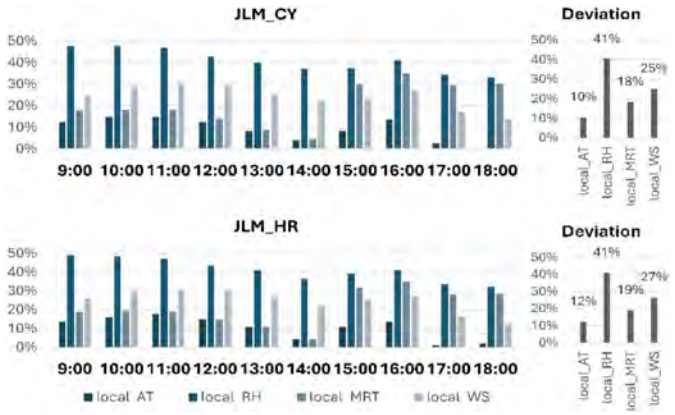


Fig. 5. RPE across typologies for UTCI in Jerusalem(left) and median deviation (right)

LB UTCI values in Tel Aviv for both courtyard and high-rise typologies, as shown in Fig. 6, range from 26–29 °C (moderate heat stress), whereas ENVI-met UTCI values range from 26–33 °C (moderate heat stress). The relatively high humidity levels in Tel Aviv are assumed to contribute to the smaller discrepancy observed between ENVI-met

and LB UTCI results. The UTCI median hourly deviation, illustrated in Fig. 7, indicates that Relative Humidity (RH) and wind speed exhibit the least deviation from ENVI-met outputs. RH deviation is 8% in the courtyard and 6% in the high-rise typologies, while wind speed deviation is 7% in the courtyard and 10% in the high-rise. These findings suggest that RH and wind speed are the most influential variables governed by local surroundings in the Tel Aviv climatic context on a summer design day.

Hourly averaged ENVI-met UTCI results for the selected analysis points as shown in Figs. 4 and 6 in Jerusalem and Tel Aviv at 14:00 show a drop across typologies of about 2–5 °C. This drop can be attributed to the shade from the higher buildings on the south-west of the simulated test site. In Tel Aviv at 10:00 there is a difference between courtyard (30.9 °C UTCI) and high-rise (26.23 °C UTCI) (Figs. 4 and 6). Upon further analysis, this difference could be due to the wind flow that was blocked by the form of the courtyard compared to the high-rise that allowed stronger and more direct airflow.

This difference in the climatic behaviour may be attributed to the fact that Tel

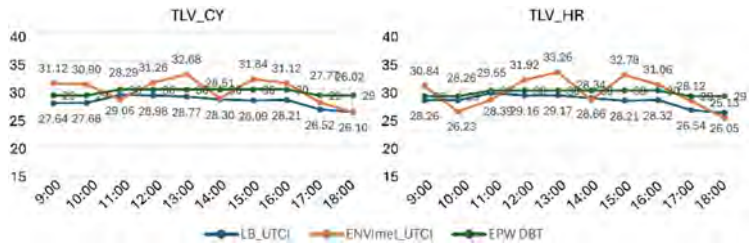


Fig. 6. Tel Aviv UTCI results for Courtyard and High Rise

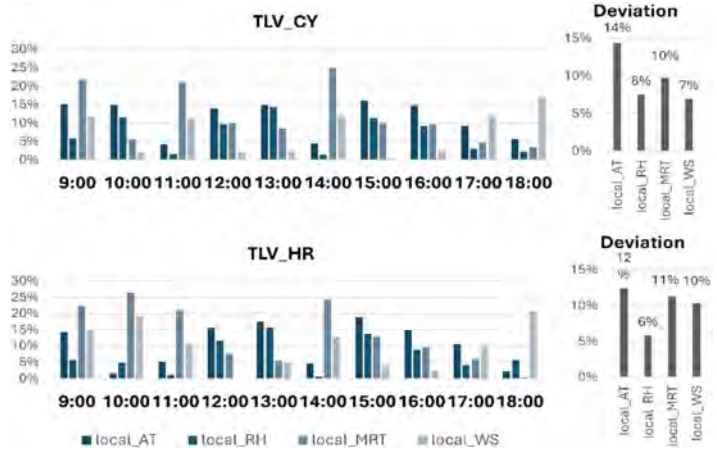


Fig. 7. RPE across typologies for UTCI in Tel Aviv (left) and median deviation (right)

Aviv, being a coastal city, exhibits higher wind speeds in the EPW data. When these wind speeds are directly used in the UTCI calculation, the cooling effect of trees appears reduced, as stronger winds can diminish the localized impact of transpiration.

4 Conclusions

This study investigated the influence of trees simulated as shading elements (using Ladybug Tools) and as biological systems (using ENVI-met) on OTC. Simulations were conducted across two Mediterranean climatic contexts of Tel Aviv and Jerusalem for two building typologies (courtyard and high-rise) with a constant FAR of 6 as representative of the case study neighbourhood.

In Jerusalem, ENVI-met predicts significantly higher UTCI values than Ladybug, with differences of about 10 °C across typologies, likely due to its inclusion of vegetation-induced humidity and reduced wind flow. Air temperature and MRT show the smallest deviations (10–12% and 18–19%), making them the most influential variables. In Tel Aviv, both tools indicate moderate heat stress with smaller differences, likely due to consistently high humidity. Here, relative humidity and wind speed show the least deviation (6–8% and 7–10%), indicating their dominance. At 10:00, the courtyard shows higher UTCI (30.9 °C) than the high-rise (26.2 °C) due to restricted airflow.

This study is limited to two building typologies with a constant FAR of 6 in a specific case study, but they contribute to understanding of early-stage design decisions in urban form. The study adopts a comparative modelling approach and does not include empirical validation; results should therefore be interpreted in relative rather than absolute terms. Future work will expand the parameter space to include additional building and vegetation attributes, assess impacts on building energy performance, and validate simulation results. Overall, these findings highlight the importance of representing vegetation as an active climatic agent in early-stage urban design workflows and also align with circular economy principles by promoting vegetation as a regenerative, low-impact strategy that enhances environmental performance while supporting resource-efficient urban design.

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Mapping Agricultural Residues as Sources for Low-Carbon Concrete Production: A Spanish Case Study

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Abstracts. Concrete is the most widely consumed human-made material worldwide and a major contributor to environmental impacts in the construction sector. Its sustainability is primarily challenged by the production of Portland cement, responsible for approximately 5–8% of global anthropogenic greenhouse gas emissions due to clinker calcination and high energy demand. Recent research has explored supplementary cementitious materials (SCMs) as partial clinker substitutes, thereby reducing carbon intensity and promoting circular economy practices. SCMs include industrial by-products (e.g. fly ash or ground granulated blast-furnace slag), natural minerals (e.g. volcanic ash or metakaolin), and agricultural residues (e.g. rice husk ash, sugarcane bagasse ash or maize cob ash). Biomass-derived materials have shown potential to maintain or even improve concrete performance when incorporated at substitution rates typically below 20%, while contributing to emission reductions in cement production. Building on this literature, the present study examines the Spanish context to evaluate the availability and geographical distribution of agricultural residues most suitable for use as SCMs. Following a rigorous screening process to identify biomass-derived materials with appropriate chemical and mechanical properties for concrete applications, the spatial distribution of these resources is assessed. The methodology employs Geographic Information Systems (GIS) to map crops and associated residues around a cement plant in Spain, enabling the identification of high-potential biomass streams. This study provides a territorial baseline to support future experimental validation, life-cycle assessment, and region-specific substitution strategies. The results contribute to advancing low-carbon and circular construction practices by establishing the resource foundations necessary for integrating agricultural residues into concrete production.

Keywords: Low-Carbon Concrete · SCMs · Agricultural Residues · Residue-Based Materials · Circular Economy

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1 Introduction

Concrete is one of the most important materials in modern construction, being the second most widely used substance after water and the most widely consumed human-made material [1, 2], owing to its versatility, durability, and the possibility of producing it with locally available raw materials. The large quantities in which it is used have called its sustainability into question [1], making the concrete industry one of the largest consumers of natural resources worldwide.

Traditionally, concrete is produced by combining Portland cement, water, aggregates (sand and gravel), and chemical admixtures that enhance workability and performance. Among all these components, cement stands out as the principal constituent of concrete and, at the same time, its largest source of environmental impact [2]. In fact, cement production is responsible for approximately 5–8% of anthropogenic greenhouse gas (GHG) emissions [3–5]. This is because, for each tonne of clinker produced, roughly 850 kg of CO_2 are emitted [6], the majority of which results from the decomposition of $CaCO_3$ to produce CaO, a process that releases CO_2. In addition to GHG emissions, cement production entails significant other environmental impacts, stemming from the large quantities of natural resources required for its manufacture [6] and from the generation of process residues.

With global demand for cement expected to rise between 12–23% by 2050 compared to 2020 levels [7], it is imperative to explore mitigation strategies to reduce associated environmental impacts.

In this context, rethinking concrete production from a sustainability and circular economy perspective is essential. One promising strategy involves the use of supplementary cementitious materials (SCMs) to partially replace cement or some of their components. These materials, ranging from industrial by-products and natural minerals to processed agricultural residues, can reduce the carbon intensity of concrete while maintaining its technical performance [3].

Furthermore, agricultural residues represent an increasingly relevant stream within the circular economy framework. In many regions, inadequate waste management practices have led to severe health risks and significant environmental degradation [8]. Meanwhile, ashes from many biomass by-products contain high concentrations of silica, which can exhibit strong pozzolanic activity when subjected to controlled combustion processes [2]. Consequently, the valorisation of agricultural residues as SCM offers a dual benefit: mitigating environmental impacts associated with waste disposal while reducing resources consumption and the carbon footprint of concrete.

Despite growing interest in agricultural residues as SCMs, their large-scale implementation remains limited by the lack of systematic approaches to identify, quantify, and spatially allocate biomass resources in relation to cement production facilities. In this context, this study develops a transferable GIS-based framework to identify agricultural residues with potential use as SCMs. The workflow links parcel-scale crop distribution data with cement plants to screen geographically proximate biomass resources. It integrates land-use information, residue generation factors, and distance-based supply zones to assess spatial availability and potential clinker substitution.

To illustrate its practical applicability, the methodology is applied to a cement plant located in Aragón (Spain), serving as a case study to demonstrate how regional agricultural datasets can support the identification of alternative SCMs.

2 Methodology

This study develops a transferable GIS-based workflow to identify agricultural residues with potential use as SCMs through spatial linkage between crop distribution and cement production facilities. The methodology follows a sequential screening framework applicable in regions where parcel-level agricultural datasets are available. The steps are detailed below.

2.1 Agricultural Data Acquisition

Geospatial agricultural data are retrieved from national Land Parcel Identification Systems (LPIS), which provide official parcel-level crop declarations submitted under the Common Agricultural Policy. These databases contain georeferenced agricultural parcels together with declared crop types and cultivated surface areas.

Equivalent LPIS-based systems operate across all EU Member States (MS), ensuring harmonised parcel identification and crop declaration procedures. Examples include the Registre Parcellaire Graphique and the Integriertes Verwaltungs- und Kontrollsystem, which support the transferability of the methodology to other MS.

2.2 Data Processing and Cultivated Area Quantification

Parcel-level crop datasets are processed through automated geospatial analysis routines to ensure reproducibility and scalability. The workflow consists of extracting declared agricultural parcels, aggregating cultivated surface area by crop category within predefined administrative or supply boundaries, and standardising crop classifications according to official coding systems available in each national database.

2.3 Spatial Linkage with Cement Plants

The transport distance between residue sources and cement manufacturing facilities constitutes a key parameter within the proposed methodology. Life-cycle assessment studies highlight transportation as a significant contributor to environmental impacts in resource valorisation systems [9], while transport costs strongly influence economic feasibility. Both aspects are closely linked to the selected transport mode, with road transport typically dominating short-to-medium distance biomass supply chains.

As specific sourcing distances for SCMs from agricultural residues are rarely reported, transport ranges used in biomass logistics and alternative fuel studies were adopted as an analogous framework. Literature suggests a biomass supply radius of 40–50 km is economically reasonable for untreated, low-density residues, extending up to 100 km for higher-value or pre-processed biomass [10]. These distances also

support regional circular economy strategies by favouring local sourcing and reducing transport-related impacts. Based on this evidence, two indicative supply zones are defined around cement plants: (i) Primary supply area: 0–50 km and (ii) Regional supply area: 50–100 km.

These zones are implemented through GIS buffer analysis to identify agricultural parcels located within environmentally and economically realistic sourcing distances, while promoting local circular economy strategies.

2.4 Screening of Potential Pozzolanic Residues

For crops identified within the defined influence areas, a targeted literature review was conducted to determine whether associated agricultural residues have demonstrated pozzolanic or cementitious reactivity.

The screening focused exclusively on residues previously studied as SCM precursors, considering reported chemical composition, ash reactivity and documented applications in cement or concrete production.

2.5 Prioritisation and Quantitative Estimation of Residue Availability

Following spatial identification and literature-based screening of crops with documented pozzolanic potential, a quantitative prioritisation step is undertaken to assess the practical feasibility of residue valorisation at industrial scale.

The estimated dry mass (*Rdry*) of agricultural residues available within the defined supply area is estimated using Eq. (1):

$$Rdry = A \cdot Y \cdot RPR \cdot DMF \tag{1}$$

Where: $Rdry$ = estimated dry residue mass (t/y); A = cultivated area of the crop within the supply zone (ha); Y = average crop yield (t/y ha^{-1}); RPR = residue-to-product ratio (dimensionless); DMF = dry matter fraction of the residue (dimensionless).

Y may be obtained from agricultural statistics, international databases, or official crop monitoring reports. The RPR and DMF can be sourced from internationally recognised methodological guidelines, such as the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry, which provides default coefficients for major crop types. Finally, the ash percentage for each crop is calculated from *Rdry*.

3 Case Study Application

The CEMEX Morata de Jalón facility (Zaragoza, Spain) is a high-capacity integrated cement plant with nominal clinker production exceeding 1.1 million tonnes per annum. Strategically located in the Jalón River valley, the plant leverages high-quality local limestone deposits characterised by high $CaCO_3$ purity and low alkali content. Within the framework of the European Green Deal, the facility has achieved fossil fuel substitution rates above 50% through the co-processing of alternative fuels and carbon-neutral biomass. Its role as a regional waste-valorisation hub and its proximity to high-density cereal crops make it an ideal candidate for evaluating the integration of biomass-derived SCMs.

3.1 Agricultural Data Acquisition

For this case study, 2024 crop declaration datasets from the Spanish LPIS (SIGPAC) were downloaded province by province in GeoPackage (GPKG) format.

3.2 Data Processing and Cultivated Area Quantification

Provincial geospatial files were first read and agricultural parcels extracted. Cultivated areas were then aggregated by crop type, and official crop names were assigned using the COD_PRODUCT classification. The processed datasets were exported for subsequent spatial analyses, enabling the identification of dominant crops within the supply zones surrounding the cement plant.

3.3 Spatial Linkage with Cement Plants

A circular supply area with a 50 km radius was defined around the plant to represent the sourcing zone for agricultural residues (Fig. 1). This distance was selected assuming biomass is transported untreated, with on-site processing at the cement facility.

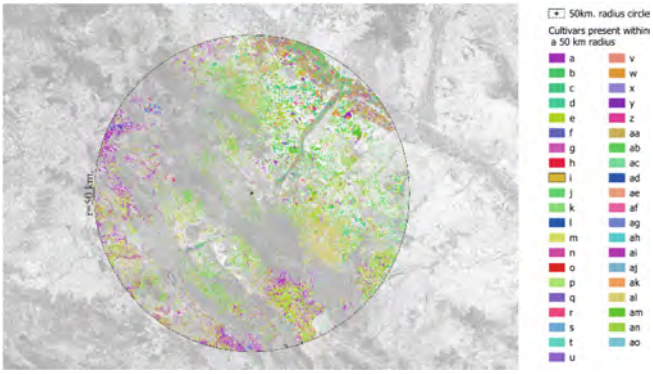


Fig. 1. Parcels and crops in the study area, based on the author's own GIS analysis.

The main crops present within the radius are listed below, and their cultivated area is presented in Table 1: common wheat (a), spelt (b), durum wheat (c), maize (d), barley (e), rye (f), sorghum (g), oats (h), buckwheat (i), canary seed (j), triticale (k), teff (l), sunflower (m), oilseed rape (n), camelina (o), pea (p), broad bean (q), bean (r), chickpea (s), lentil (t), vetch (u), bitter vetch (v), lucerne (w), sainfoin (x), fescue (y), perennial ryegrass (z), Italian ryegrass (aa), beet (ab), hop (ac), linseed (ad), hemp (ae), safflower (af), flowers (ag), Romanesco (ah), aromatic herbs (ai), potato (aj), olive tree (ak), vineyard (al), almond tree (am), poplar (an), holm oak (ao).

Table 1. Cultivated area (ha) of the main cultivars within a 50 km radius, based on the author's own GIS analysis.

Crop	a	b	c	d	e	f	g	h	i
Area (ha)	28,163	59	13,129	3,101	55,734	3,551	107	2,163	2
Crop	j	k	l	m	n	o	p	q	r
Area (ha)	4	15,098	4	5,457	1,108	172	3,248	313	2
Crop	s	t	u	v	w	x	y	z	aa
Area (ha)	97	53	1,665	3,647	11,886	1,567	499	309	209
Crop	ab	ac	ad	ae	af	ag	ah	ai	aj
Area (ha)	13	1	4	3	848	1	1	8	144
Crop	ak	al	am	an	ao				
Area (ha)	4,802	23,049	27,017	305	400				

3.4 Screening of Potential Pozzolanic Residues

A technical screening identified crops with reported SCM potential, excluding those used solely as aggregate or fibre. Among the identified crops in Sect. 3.3, cereal residues show the most consistent evidence of pozzolanic activity. Wheat straw ash has been widely reported to achieve cement replacement levels of 10–20% without significant loss of mechanical performance, provided controlled calcination conditions are applied [2, 11]. Similar replacement ranges have been documented for maize-derived ashes, with satisfactory strength and durability results [2, 11, 12]. Barley and oat husk ashes have also been reported as reactive siliceous materials suitable for partial cement substitution [11, 13]. Sunflower stalk and seed shell ashes have demonstrated promising behaviour, typically at lower replacement ratios (2.5–10%) [13, 14]. In all cases, practical implementation remains dependent on combustion control, ash consistency, impurity management and compliance with cement standards. Other crops identified, including oilseeds, legumes, forage crops, horticultural products, and woody species, lack sufficient experimental evidence supporting their use as cement replacement SCMs and were therefore excluded from the quantitative assessment.

Based on this technical filtering, only wheat, barley, maize, oat, and sunflower residues were considered in the subsequent mass availability assessment.

3.5 Prioritisation and Quantitative Estimation of Residue Availability

Dry agricultural residues were estimated using Eq. (1) for the crops selected in Sect. 3.4. The Y was obtained from the ESYRCE 2024 report for rainfed crops (except for maize), using the five-year average [15]. RPR and DMF were obtained from [16], except for sunflower, for which both RPR and DMF were sourced from [17].

The resulting estimates of dry residue availability within the 50 km supply radius around the Morata de Jalón cement plant are presented in Table 2. These values represent the theoretical mass of residues that could be potentially valorised as SCM.

Table 2. Estimated dry residues of selected crops within a 50 km supply radius.

Product	*A* (ha)	*Y* (t/ha)	*RPR*	*DMF*	*Rdry* (t/y)
Wheat (all varieties)	41,294	2,982	1.3	0.82–0.88	136,070
Barley	55,734	2,623	1.2	0.82–0.88	149,114
Maize	3,101	13,246	1.0	0.70–0.86	32,038
Oat	2,163	1,631	1.3	0.92	4,220
Sunflower	5,457	0,97	2.0	0.90	9,527

Applying ash content factors (6.0% for barley and 6.5% for wheat, dry basis), the theoretical availability of reactive ashes within the 50 km radius of the Morata de Jalón plant is estimated. The combined contribution of barley and wheat straw yields approximately 17,790 t/y of SCMs (8,946 t and 8,844 t, respectively). Under the assumed scenario, this could satisfy 4.6–7.7% of the annual pozzolan demand for CEM II/B-P production (21–35% pozzolanic addition). This local sourcing strategy reduces environmental and economic costs associated with long-distance transport of SCMs such as coal fly ash, which is becoming increasingly scarce in Spain. Assuming effective integration into cement production and an emission factor of 850 kg CO_2/t clinker, this pathway could mitigate up to 15,121 t of CO_2 annually.

4 Conclusions

The proposed GIS-based workflow enables reproducible identification and quantification of agricultural residues as SCMs, linking crop data, pozzolanic screening, and supply zones. Its transferability allows use in regions with parcel-level datasets.

In the Morata de Jalón case study, the methodology identified a significant local supply of wheat and barley residues within a 50 km radius, capable of producing nearly 18,000 t of reactive SCMs per annum. Limiting the number of selected residues simplifies logistics and on-site SCM preparation.

This local supply provides a strategic alternative to the increasing scarcity of coal fly ash in Spain. The potential to reduce total clinker consumption by 1.6%, satisfy up to 7.7% of the pozzolanic demand, and mitigate over 15,000 t of CO_2 annually demonstrates that regional circular models are technically and environmentally viable. These agricultural-to-cement pathways may support alignment with EU Green Deal decarbonisation targets, although further experimental validation and full life-cycle assessment remain necessary.

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Simplified Multicriteria Method for Selecting Urban Drainage Alternatives: Development and Application of the IAPD

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Abstract. Urban drainage design in the public sector is often limited by institutional constraints, scarce data, and shallow networks that hinder conventional pipe expansion. This paper introduces the Urban Drainage Project Alternative Selection Index (IAPD), a multicriteria method developed to support transparent decision-making. The methodology employs the Analytic Hierarchy Process (AHP) to weigh hydraulic, economic, environmental, and resilience criteria. The index was applied to a case study on Conde de Bonfim Street (Rio de Janeiro), comparing a conventional pipe upgrade (Grey) against a distributed system of 12 rain gardens as a Nature-Based Solution (NBS). Results indicate that the NBS alternative achieved a superior score (0.81) compared to the grey solution (0.44). The NBS proved to be 38% more cost-effective by avoiding extensive excavations in the shallow 0.95 m network. Furthermore, the hybrid approach demonstrated superior resilience, using source control to prevent the saturation of existing pipes rather than merely increasing conveyance capacity. The IAPD fulfills its role as a defensible tool for public managers to justify sustainable, nature-based investments in constrained urban environments.

Keywords: Urban Drainage · Nature-Based Solutions · Multicriteria Decision-Making · Stormwater Management · Sustainable Built Environment

1 Introduction

The urbanization process in Brazilian cities, such as Rio de Janeiro-RJ, has led to a significant increase in surface runoff, creating a demand for engineering projects that meet society's expectations. This process, associated with extreme hydrological events, accelerates runoff and peak flows, requiring a strategic shift from traditional drainage to integrated water management practices Tucci [11]. According to Castro [1], selecting the appropriate project typology is urgent, as inadequate designs can increase runoff velocity and, consequently, amplify negative impacts on the urban drainage system.

For Macedo et al. [2], various techniques can be applied within the urban territory to address drainage issues. However, the selection process must account for technical criteria and constraints that vary according to local specificities. Therefore, the choice

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of technique should be based on multi-criteria decision models applied at a spatial scale [2]. According to Mendonça [3], multi-criteria analysis in the context of flood control and urban drainage is a vital method for supporting decision-making processes, due to its ability to simplify analyses involving multiple objectives and interests. Nevertheless, implementing such analyses requires tools that allow for a deeper evaluation of the studied spheres.

In this context, this paper proposes the Urban Drainage Project Alternative Selection Index (IAPD) as a decision-support tool. The main objective of this study is to evaluate the applicability of the IAPD in a high-density urban environment, using the Tijuca neighborhood in Rio de Janeiro as a case study. Specifically, this research aims to: (i) analyze the integration of hydraulic and economic criteria in the selection of drainage alternatives; and (ii) demonstrate how the index can simplify the decision-making process for public managers in resource-constrained scenarios. This paper is organized as follows: Sect. 2 describes the methodology; Sect. 3 presents the case study; Sect. 4 discusses the results; and Sect. 5 draws the final conclusions.

2 Methodology

The proposed methodology provides a systematic, multi-criteria framework for selecting urban drainage infrastructure under data and physical space constraints. The process integrates criteria selection, strategic weighting aligned with public administration standards, and a composite index calculation to support objective decision-making through a three-stage analytical workflow: (i) definition of performance pillars; (ii) hierarchical prioritization; and (iii) mathematical integration.

2.1 Multicriteria Framework and Criteria Selection

A Multi-Criteria Decision Analysis (MCDA) was adopted to evaluate the trade-offs between technical efficiency and economic feasibility. The Urban Drainage Project Alternative Selection Index (IAPD) is composed of four core indicators selected for their relevance to public sector management: (i) Hydraulic Performance (HP), evaluating peak flow attenuation; (ii) Life-Cycle Cost (LCC), encompassing Capital (CapEx) and Operational (OpEx) expenditures; (iii) Environmental Benefit (EB), monetized via the Avoided Costs Method; and (iv) Risk and Resilience (RR), assessing infrastructure vulnerability to extreme climate events and operational failures.

2.2 The AHP Weighting and IAPD Formulation

Criteria weighting was performed using the Analytic Hierarchy Process (AHP) to ensure logical consistency, following the fundamental principles of multicriteria decision-making defined by Saaty [12]. Departing from uniform distributions, this study adopted a Strategic Public Governance Perspective informed by the Brazilian New Bidding Law (Law No. 14,133/2021) [4]., which mandates the evaluation of life-cycle efficiency and risk allocation in high-complexity projects. Consequently, higher relative importance was assigned to Economic and Risk criteria, as detailed in Table 1.

Table 1. IAPD criteria, descriptions, and theoretical weights.

Criterion	Weight (wi)	Technical Justification
Economic (LCC)	**0.35**	Prioritizes long-term fiscal responsibility and life-cycle efficiency.
Risk (RR)	**0.30**	Addresses mandatory risk matrices and climate adaptation resilience.
Hydraulic (HP)	**0.20**	Ensures minimum technical standards for flood mitigation are met.
Environmental (EB)	**0.15**	Validates ecosystem services as institutional added value.
TOTAL	**1.00**	

The final ranking of alternatives is generated by Eq. (1), which consolidates the normalized indicators:

$$IAPD = \sum_{i=1}^{n} (wi * Ii) \tag{1}$$

Where Ii represents the normalized indicator score (0–1 scale) and wi denotes the strategic weight derived from the AHP matrix.

2.3 AHP Consistency and Data Normalization

To guarantee reproducibility, indicators were normalized according to their functional nature. Cost-type criteria, such as Life Cycle Cost (LCC), follow the relationship Ii = (Min / Value). Conversely, benefit-type criteria, including Hydraulic Performance (HP), Environmental Benefits (EB), and Risk and Resilience (RR), follow the relationship Ii = (Value / Max). The RR score was determined through a semi-quantitative matrix aligned with the ISO 31000 [14] framework, defined as the product of event frequency and impact severity (Risk = Frequency × Severity). This value was then inverted to represent resilience levels, ensuring that higher scores reflect better performance within the 0 to 1 normalized range. This framework aligns with the research developed by the Sistemas de Águas Urbanas group at UERJ (Ohnuma Júnior et al. [13]).

3 Case Study: Conde de Bonfim Street, Rio de Janeiro

3.1 Site Characterization and Problem Identification

The IAPD index was applied to a strategic urban corridor in the Tijuca neighborhood, Rio de Janeiro. The analyzed segment extends along Conde de Bonfim Street, from the intersection of Aguiar Street (22°55′20.29″S; 43°13′18.35″W) to Saenz Peña Square (22°55′27.86″S; 43°13′57.35″W), utilizing the WGS84 [9] geographic coordinate system. Topographic data reveals a localized elevation gradient where Aguiar Street is at 14.00 m above sea level and Saenz Peña Square is at 15.00 m [5, 9]. The selection of this

specific region is justified by its high soil surface impermeability and recurrent localized flooding, which demand urgent infrastructure upgrades. Furthermore, this corridor serves as a major arterial route for underground utilities, where the existing drainage network (DN 300 mm to 400 mm) is situated at a shallow average depth of 0.95 m [5]. Under the framework of Law No. 14,133/2021 [4]., this scenario presents a high Institutional and Construction Risk (RR), as capacity expansion via traditional methods would require complex and costly relocation of telecommunications, gas, and water supply lines.

3.2 Alternative A: Conventional Pipe Upgrade (Grey Infrastructure)

Alternative A consists of replacing the undersized existing network with a new DN 600 mm concrete pipeline, dimensioned to meet the hydraulic requirement for a 10-year return period (TR), as established by the Rio-Águas Drainage Instructions Manual [5]. According to technical standards for minimum cover and hydraulic slope, this solution requires an excavation depth of 1.80 m, which drastically exceeds the 0.95 m elevation where underground utility interferences (gas, water, and telecommunications) are located, as identified in the technical registry [5]. Implementation costs were derived from the EMOP Price Table (2026) [7], resulting in a CAPEX of R$ 1,120,000.00. Due to the encroachment on the existing utility cota, this alternative is penalized with an estimated R$ 350,000.00 for utility relocation, increasing both execution risk and total life-cycle cost, in accordance with the risk matrix criteria of Law No. 14,133/2021.

3.3 Alternative B: Distributed Rain Gardens (Nature-Based Solution - NBS)

Alternative B proposes the implementation of 12 distributed rain gardens designed to attenuate the peak flow for the same 10-year return period, complying with Rio-Águas [5] regulatory requirements and following the experimental parameters defined by Gondim (2024) [6]. This solution focuses on source runoff control, reducing the surcharge on the existing network without requiring full pipe replacement. Budgetary values were extracted from the CGEE. Technical Note (2026) [8], resulting in a CAPEX of R$ 610,000.00. By maintaining a design depth of only 0.60 m, this alternative remains above the critical utility cota (0.95 m), reducing relocation costs to R$ 45,000.00. This approach meets the fiscal efficiency principles of Law No. 14,133/2021 while promoting superior environmental benefits (EB) through ecosystem services.

4 Results and Discussion

The performance of the drainage alternatives was evaluated by contrasting the physical constraints of Conde de Bonfim Street with the strategic requirements of the Brazilian New Bidding Law (Law No. 14,133/2021) [4]. Table 2 summarizes the primary engineering and financial parameters, providing the empirical basis for the multicriteria analysis.

As shown in Table 2, Alternative A is significantly impacted by the 1.80 m excavation requirement in a zone with a shallow existing network (0.95 m). This physical constraint

Table 2. Technical and Economic parameters for Alternatives A and B.

Attribute	Unit	Alternative A (Grey)	Alternative B (NBS)
Implementation Cost (CAPEX)	R$ (10^3)	1,120.00	610.00
Annual Maintenance (OPEX)	R$ (10^3)	15.00	22.00
Utility Relocation Cost (Risk-based)	R$ (10^3)	350.00	45.00
Total Life-Cycle Cost (LCC - 20 years)	R$ (10^3)	1,770.00	1,095.00
Peak Flow Reduction (Delta Q)	%	85%	72%
Excavation Depth	m	1.80	0.60

Source: Prepared by the author (2026), based on EMOP (2026) [7], CGEE (2026) [8], and Rio-Águas (2025) [5].

Table 3. Normalized IAPD indicators (Scale 0–1).

Indicator	Alt A (Grey)	Alt B (NBS)	Normalization Rationale
Hydraulic (HP)	0.85	0.75	Benefit-type (Value/Max)
Economic (LCC)	0.32	0.90	Cost-type (Min/Value)
Risk (RR)	0.25	0.80	Qualitative rubric (Scale 0–1)
Environmental (EB)	0.50	0.70	Benefit-type (Scalability)

Source: Prepared by the author (2026), applying the normalization logic to data from EMOP [7] and CGEE [8].

leads to a 38% higher Life-Cycle Cost (LCC) due to mandatory utility relocation and structural risks. These attributes were normalized into the 0–1 scale presented in Table 3.

The final integration, utilizing the strategic weights derived from the implicit hierarchy of the new bidding framework (wi LCC = 0.35; wi RR =0.30; wi HP = 0.20; wi EB =0.15), resulted in the consolidated ranking presented in Table 4.

Table 4. Final Weighted IAPD Scores and Ranking

Criterion	Weight (wi)	Weighted (A)	Weighted (B)
Economic (LCC)	0.35	0.11	0.31
Risk (RR)	0.30	0.08	0.24
Hydraulic (HP)	0.20	0.17	0.15
Environmental (EB)	0.15	0.08	0.11
Final Score (IAPD)	1.00	0.44	0.81

Source: Prepared by the author (2026), based on the AHP weighting methodology established in Table 1.

The results confirm that Alternative B (NBS) is the most efficient choice for the study area. This finding corroborates Baptista, Nascimento, and Barroud (2011) [10]. regarding the economic advantages of source-control techniques in dense urban environments, where traditional "end-of-pipe" solutions face severe physical limitations. As argued by Mendonça and Souza (2019) [3], decision-making in urban drainage must transcend purely hydraulic metrics to include operational and fiscal sustainability. The high Risk and Resilience (RR) score for the NBS reflects its ability to bypass underground utility interferences, a critical factor for compliance with the "best value" and risk-aversion principles of Law 14,133/2021 [4]. Furthermore, the economic viability of the NBS is supported by standardized pricing frameworks; while Alternative A's costs were validated against the EMOP (2026) [7]. reference tables, the budgetary feasibility of the distributed rain gardens aligns with the specialized Nature-Based Solutions guidelines from CGEE (2026) [8]. By integrating these official budgetary references with the climate resilience goals described by Gondim (2024) [6], the NBS proved to be a more defensible and fiscally responsible solution for the Conde de Bonfim sub-basin, ensuring that environmental externalities are coupled with rigorous public sector cost-accounting

5 Conclusions

The present study achieved its primary objective by developing and applying the Urban Drainage Project Alternative Selection Index (IAPD), providing a multicriteria framework strictly aligned with the strategic requirements of the Brazilian New Bidding Law (Law No. 14,133/2021). By integrating hydraulic performance with life-cycle efficiency and risk allocation, the index offered a transparent and data-driven path for infrastructure prioritization in dense urban environments characterized by severe physical constraints. The application of this methodology to the Conde de Bonfim case study produced robust numerical results that confirm Alternative B, the Nature-Based Solution (NBS), as the most effective and defensible choice for the study area.

The superiority of the NBS is evidenced by its final IAPD score of 0.81, which represents an 84% performance increase over the 0.44 score achieved by the conventional Grey Infrastructure of Alternative A. This disparity is fundamentally rooted in the economic efficiency and risk mitigation capacity of decentralized systems. While the conventional upgrade required a total life-cycle cost of R$ 1.77 million, the distributed rain gardens achieved a 38% reduction in public expenditure, totaling R$ 1.09 million over a 20-year horizon. This fiscal advantage is directly linked to the avoidance of high-risk excavations; by maintaining a shallow design depth of 0.60 m, the NBS bypassed the costly relocation of underground utilities that severely penalized the 1.80 m depth required for the traditional pipe expansion.

Ultimately, the IAPD framework successfully translated the legal principles of "best value" and "institutional security" into a reproducible engineering tool. The study confirms that for urban watersheds with high interference from existing infrastructure, Nature-Based Solutions are not only environmentally superior but also the most fiscally responsible decision for municipal managers under the current Brazilian regulatory framework. By aligning technical excellence with risk-averse legal requirements, the proposed methodology ensures that urban drainage investments contribute effectively to both long-term climate resilience and the efficient management of public resources.

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Overheating Risk in Naturally Ventilated Student Dormitories: An Analysis Based on Real-Time Indoor Environmental Data and Climate Scenarios

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Abstract. Due to anthropogenic effects, the world is facing unusual temperature fluctuations and increasingly frequent heat waves that represent a significant shift in urban weather patterns, affecting building energy loads. Student dormitories in Türkiye, like many residential buildings, typically operate without mechanical cooling systems and rely solely on natural ventilation. This adversely affects thermal comfort during summer months and is likely to worsen in the coming years. This study combines real-time indoor monitoring data, calibrated building energy modeling, and climate projections to examine current and future overheating trends in naturally ventilated student rooms. A representative student room was calibrated using indoor temperature and window-opening behavior data obtained from the Energy Management System (EMS) installed in Dormitory 6, Block B at our university as part of the LEGOFIT Horizon Europe project. The model was used to assess current thermal performance, adaptive comfort conditions, and overheating indicators. Simulations were conducted for different years and climate scenarios to analyze the effects of projected temperature increases on overheating risks. Under current conditions, temperatures in naturally ventilated rooms can rise considerably, particularly under high-emission scenarios. Furthermore, students' behaviors, such as window-opening patterns, and occupancy density were found to have a critical impact on indoor temperature variations. These findings highlight the importance of campus-wide strategies to be developed and provide a scientific basis for climate change adaptation planning.

Keywords: Thermal Comfort · Overheating Risk · Natural Ventilation · Building Energy Modeling · Student Dormitories · Climate Change Scenarios

1 Introduction

Anthropogenic climate change is one of the primary drivers making thermal comfort conditions in building interiors increasingly precarious, as the frequency and intensity of heat waves continue to rise [1, 2]. Future climate scenarios predict an increased risk of overheating in naturally ventilated buildings and a decrease in the effectiveness of

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current passive strategies [3]. Student dormitories typically lack mechanical cooling, making indoor conditions highly dependent on user behavior [4]; thus, envelope-only simulations fail to represent real-world operating conditions. For overheating analyses in free-running buildings, the adaptive thermal comfort approach provides more consistent results compared to fixed threshold values [5, 6]. While most studies in the literature are simulation-focused or based on short-term measurements, research integrating real-time monitoring data, calibrated dynamic models, and future scenarios is limited. In this context, "energy resilience" addresses a building's capacity to maintain its performance in changing climatic conditions with a temporal trend [7, 8]. This study develops a calibrated IESVE model using EMS data from the LEGOFIT project and evaluates the temporal energy and comfort resilience of natural ventilation and alternative strategies under RCP4.5 and RCP8.5 scenarios.

2 Methodology

The temporal energy and comfort resilience approach developed in the study combines (i) the increased risk of overheating under future climate scenarios, (ii) the capacity of systems to maintain their performance limits in the face of external pressures (resilience), and (iii) time-dependent degradation rate analyses in engineering systems [8, 9]. With this synthesis, building performance is evaluated through a temporal evolution curve in the face of climate exacerbation, instead of a static reference year. The proposed integrated structure includes a calibrated dynamic building model, user-oriented window opening profiles, and climate projections for different emission scenarios. The research process consists of model calibration, definition of intervention strategies, performance of dynamic simulations, and analysis of results with temporal performance indicators.

2.1 Reference Building Modeling and Calibration

In this study, a single student room in Block B of Dormitory 6 at Özyeğin University was modelled using the IESVE simulation platform (Fig. 1). Thermal balance calculations follow the principles of EN ISO 52016-1 and EN ISO 13790. Internal gains were defined for occupants (6.8 W/m^2), lighting (6 W/m^2), and other equipment (8 W/m^2). Model calibration followed ASHRAE Guideline 14 criteria [10]. Monthly electricity and natural gas consumption were validated using NMBE ($\pm$5%) and CVRMSE ($\leq$15%) indicators, while natural ventilation parameters were verified against monitored summer indoor temperature data. This approach ensured model reliability for both energy and thermal performance. The reference building envelope complies with Turkish TS 825 standards, featuring an external wall (U = 0.34 W/m^{2}K), a flat roof (U = 0.31 W/m^{2}K), and intermediate floors (U = 0.51 W/m^{2}K). Envelope airtightness was assumed as 3.0 ACH50 in accordance with TS 825. Natural ventilation rates were derived from project monitoring data and implemented using the IESVE MacroFlo module. The air exchange rate was defined as 0.4 h^{-1} with windows closed and 3.8 h^{-1} when open, allowing the model to capture realistic user-driven ventilation behaviour.



Fig. 1: Digital model of Dormitory-6 developed in IESVE and on-site EMS installation

2.2 Defining Scenario Packages

Five intervention strategies were defined to evaluate different adaptation approaches in building energy simulations. S1 (Behaviour + Night Purge) links window control to EN 16798-1 Category II, enabling night ventilation (22:00–06:00) when outdoor temperature is lower than indoor temperature (T_out < T_in). S2 (External Shading) reduces solar transmittance, while S3 (Solar Control Film) reduces glazing solar heat gain coefficient (SHGC). S4 (Glazing Upgrade) introduces low-e double glazing (U ≈ 1.2–1.4 W/m^{2}K). Finally, S5 (Hybrid Ventilation) provides assisted night ventilation under suitable outdoor conditions.

2.3 Climate Projections and Simulation Design

Performance assessment was conducted using the IPCC-defined RCP4.5 and RCP8.5 emission scenarios [11] for the period 2024–2080. Annual energy consumption and overheating duration were calculated for each period to evaluate the temporal evolution of building performance.

2.4 Overheating and Comfort Calculations

Thermal comfort was assessed using the EN 16798-1 adaptive model based on the moving average temperature of the ambient environment [12]. The risk of overheating was calculated based on the total annual hours during which the adaptive comfort upper limit was exceeded. In the assessments, a critical risk limit of 300 h/year was accepted, in accordance with CIBSE TM52 and TM59 guidelines [6, 9].

2.5 Temporal Energy Resilience Indicators

The energy consumption $E_s(t)$ defined in Eq. (1), was normalized with respect to the reference year t_0 to ensure comparability across scenarios Eq. (2).

$$E_s(t) = a_s t + b_s \tag{1}$$

$$E_s^*(t) = \frac{E_s(t)}{E_s(t_0)} \tag{2}$$

The adaptation coefficient (K_ad,s) is defined as the slope of the normalized curve. In this study, the temporal evolution of energy performance is represented using linear regression within a simplified modelling framework. The coefficient represents the average annual performance deterioration and enables comparison of long-term resilience among different strategies. Lower values indicate slower performance deterioration and therefore higher temporal energy resilience Eq. (3). The acceptable performance band for energy is defined in Eq. (4).

$$K_{ad,s} = \frac{dE_s^*(t)}{dt} \tag{3}$$

$$E_s^*(t) \leq 1 + \delta \tag{4}$$

In this study, δ was set at 15%. This threshold was chosen in accordance with the performance class degradation risks under the European Energy Performance Directive [13, 14]. The critical year (t_crit) was defined as the first time this threshold value was exceeded.

3 Result and Discussion

3.1 Model Calibration and Validation

The building model was calibrated in two stages to ensure the reliability of the climate projection analysis. Firstly, monthly electricity and natural gas consumptions were validated, where NMBE was within ±5% and CVRMSE was 15% below [10]. Subsequently, hourly indoor temperatures were simulated using EMS-based window operation profiles and MacroFlo airflow rates of approximately 3.8 air changes per hour, showing strong agreement in daily temperature amplitudes and night cooling performance. This two-scale calibration process confirms the model's reliability for long-term energy and comfort analyses (Fig. 2).

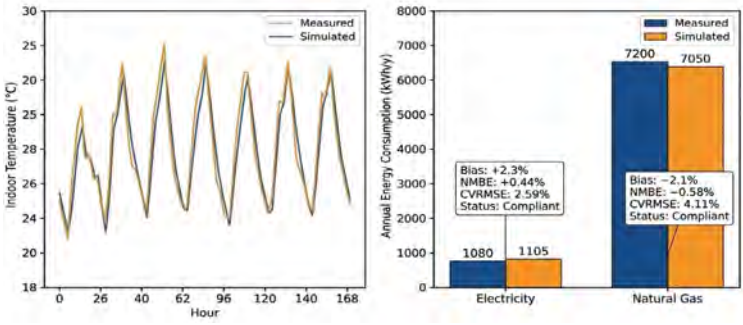


Fig. 2: Model calibration results in indoor temperature and annual energy consumption

3.2 Overheating Evolution under Climate Scenarios

The calibrated model was used to assess the trend towards extreme warming under RCP4.5 and RCP8.5 climate projections. Comfort performance was evaluated using an overheating threshold of 300 h per year [6, 10]. Under the RCP4.5 scenario (Fig. 3), overheating hours in the reference natural ventilation case gradually increase, exceeding the 300 h/year threshold around the year 2060. This suggests that natural ventilation can maintain acceptable comfort conditions in the medium term but becomes limited towards mid-century. Among all strategies, S5 provides the lowest overheating hours and the longest stability range. In the RCP8.5 high emission scenario, the tendency towards overheating accelerates significantly. In the reference natural ventilation scenario, the 300-h threshold is exceeded around the years 2040–2050, and overheating hours approach 800 h/year towards the end of the century. While passive strategies reduce the rate of increase in overheating, they cannot completely prevent exceeding the threshold on the high emission path. In contrast, the S5 strategy stands out as the most effective solution for limiting the increase in overheating, even under late-century conditions. These results highlight the importance of considering future climate impacts when assessing comfort performance. While passive interventions can provide sufficient adaptation capacity on the medium emission path, hybrid solutions with operational support emerge as a more robust option in the high emission scenario.

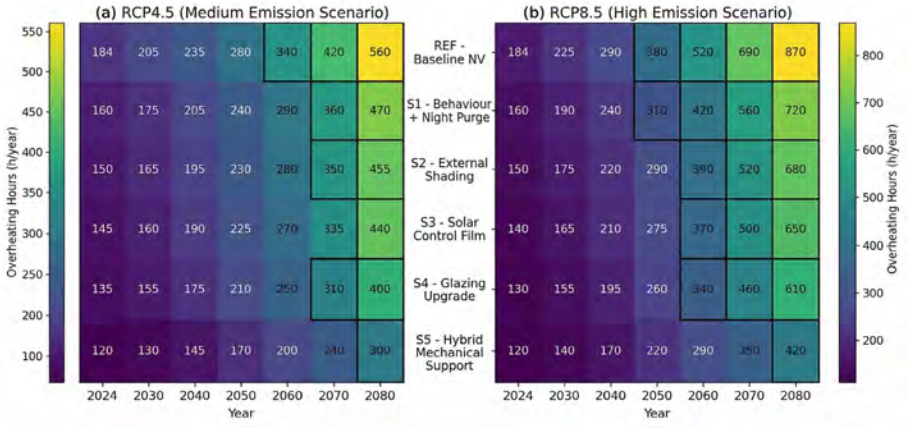


Fig. 3: Annual overheating hours under RCP4.5 and RCP8.5 scenarios

3.3 Temporal Energy Resilience Analysis

The temporal evolution of normalized energy consumption under climate change was evaluated using the adaptation coefficient (K_ad) and the critical threshold year (t_crit), based on the methodology described in Sect. 2.5. Under the RCP4.5 scenario (Fig. 4), energy consumption gradually increases under the reference natural ventilation condition, with the $\delta = 15\%$ threshold reaching around 2065. Behavioural and passive

strategies (S1–S4) slightly delay this threshold, while the S5 hybrid ventilation strategy extends the stability range until the end of the analysis period and exhibits the lowest K_ad. Under RCP8.5, the deterioration in energy performance accelerates significantly. In the reference scenario, normalized energy consumption increases by more than 50% towards the end of the century, with the critical threshold reaching around the year 2050. Although passive strategies reduce the rate of increase, they cannot fully prevent threshold exceedance under high-emission conditions. The S5 strategy shows the lowest K_ad and the longest stability range, highlighting the importance of low-energy mechanical support for long-term energy resilience.

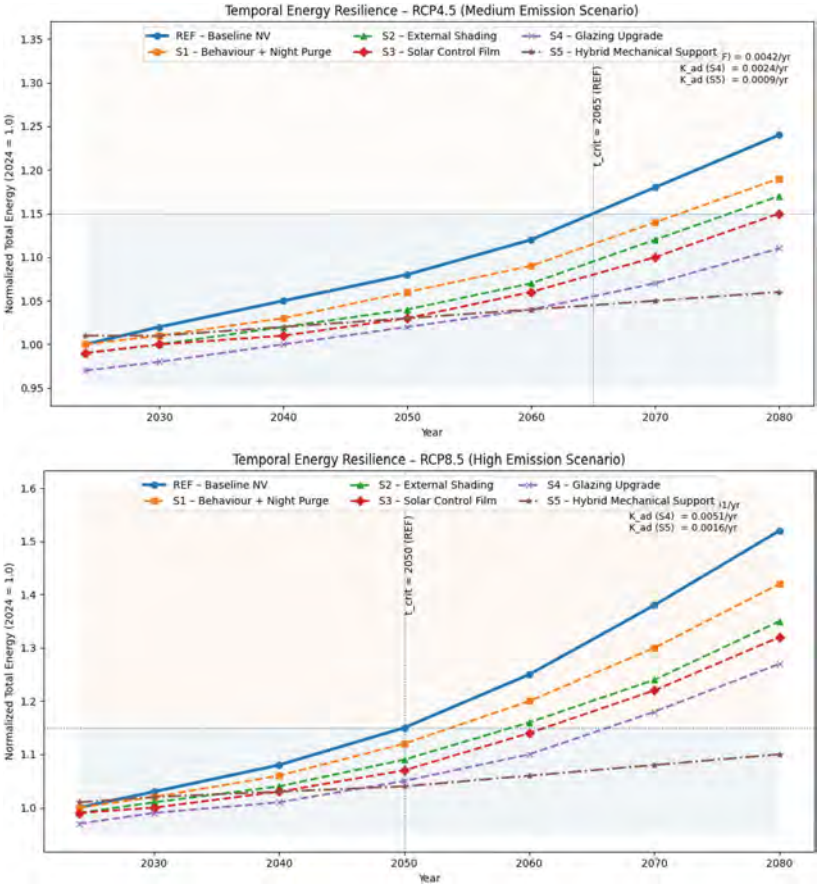


Fig. 4: Temporal evolution of normalized energy consumption under the RCP4.5 and RCP 8.5 scenarios for the strategies

3.4 Integrated Resilience Assessment

The combined evaluation of energy and comfort indicators provides a more comprehensive overview of the long-term operational stability of natural ventilation systems in the face of climate change. Table 1 shows the comparative status of each strategy in terms of both energy robustness and comfort performance. In the RCP4.5 scenario, the reference natural ventilation solution offers acceptable performance in the short and medium term. However, a temporal deterioration trend is observed in both energy and comfort indicators. Passive strategies delay threshold exceedance, reduce overheating hours, and improve energy resilience compared to the reference case. The hybrid-supported S5 stands out as the only solution that does not exceed the critical energy threshold throughout the analysis period, reducing overheating hours to 300 h/year. In the RCP8.5 scenario, the deterioration in energy performance becomes more pronounced. Under RCP8.5, performance deterioration accelerates, and passive strategies only partially mitigate threshold exceedance. These findings demonstrate that the current passive student dormitory design based on natural ventilation can remain sustainable in medium emission scenarios. However, passive intervention alone may not be sufficient in high emission scenarios. Hybrid solutions incorporating operational control and limited mechanical support provide more stable performance, especially in the second half of the century.

Table 1: Adaptation coefficients (K_ad), critical threshold years (t_crit), and projected Overheating Hours for each strategy under RCP4.5 and RCP8.5 scenarios

Strategy	K_ad (4.5)	t_crit (4.5)	OH2080 (4.5)	K_ad (8.5)	t_crit (8.5)	OH2080 (8.5)
REF	0.0042	2065	560	0.0091	2050	870
S1	0.0033	2072	470	0.0074	2054	720
S2	0.0031	2076	455	0.0062	2059	680
S3	0.0027	2080	440	0.0058	2061	650
S4	0.0024	–	400	0.0051	2066	610
S5	0.0009	–	300	0.0016	–	420

4 Conclusion

This study evaluates the energy and comfort performance of a naturally ventilated student dormitory room from a temporal resilience perspective using a calibrated dynamic model and climate projections. The model, validated with real-time monitoring data, reveals long-term performance trends under current conditions as well as RCP4.5 and RCP8.5 scenarios. Under the medium-emission pathway, acceptable performance can be maintained with passive improvements. However, under the high-emission scenario, both overheating hours and energy consumption increase significantly, indicating that passive interventions alone may be insufficient in the long term. In contrast, hybrid-supported strategies provide lower adaptation coefficients and longer stability ranges, emerging as

the most robust solution. These findings highlight the importance of evaluating building performance not only at a reference year but also in terms of its deterioration rate over time. The proposed temporal energy and comfort resilience framework can support climate adaptation planning for naturally ventilated housing types.

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Nature-Based Solutions for Flood Mitigation in a Coastal Brazilian City

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Abstract. Climate change has intensified extreme hydrological events in urban centers, particularly in coastal cities that have undergone historical processes of impermeabilization, landfilling, and suppression of natural ecosystems. The city of Vitória, capital of Espírito Santo, located in the Southeastern region of Brazil, experiences recurrent flooding episodes associated with intense rainfall. These events are exacerbated when heavy rains coincide with high tides, reducing the discharge capacity of the stormwater system, while projected sea level rise tends to further intensify these occurrences. The Administrative Region of Jucutuquara, located in a densely urbanized coastal area of the city of Vitória, presents heightened vulnerability due to occupations over former flood-prone zones and the low infiltration capacity of its soil, resulting in overload of the urban drainage system. This study aims to analyze the environmental and urban conditions of this region and propose climate-adaptation solutions based on contemporary approaches to water-sensitive urban planning. The methodology includes historical and cartographic analysis, field inspections, and an integrated diagnosis of areas susceptible to flooding. The proposed solutions are structured upon the concepts of Green-Blue Infrastructure, Sustainable Urban Drainage Systems (SUDS), Low Impact Development (LID), and Water Sensitive Urban Design (WSUD). The results indicate that these solutions can contribute to reducing surface runoff, increasing retention capacity, and strengthening local climate resilience. The study provides guidance for sustainable urban planning in Brazilian coastal cities and reinforces the need for environmental management in the face of climate change.

Keywords: Green-Blue Infrastructure · Water-Sensitive Urban Planning · Urban Climate Resilience · Sustainable Drainage Systems · Urban Flood Mitigation

1 Introduction

Climate change has been exacerbating hydrological risks in urban areas, particularly in coastal cities. In this context, the intensification of extreme precipitation events and rising sea levels are among the processes contributing to increased urban flooding, highlighting the limitations of traditional planning and drainage models [1, 2]. These impacts tend to

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be more severe in areas where urbanization has historically disregarded natural drainage systems [3, 4].

Throughout the 20th century, urban development in many coastal cities was marked by practices such as extensive soil sealing, the filling in of floodplains, and the channeling or burying of watercourses. Although these interventions were justified by public health, transportation, and urban expansion objectives, they resulted in the progressive loss of the natural capacity for stormwater retention, infiltration, and dissipation [5–7]. Consequently, the risks of waterlogging and flooding intensify in areas where natural drainage systems have been eliminated or profoundly altered. This process can be understood as the disappearance of water in urban spaces, characterized by the physical concealment of water bodies and the reduction of their ecological, hydrological, and landscape functions [1, 8].

Historically, waterways have played a fundamental role in shaping cities, guiding land use and natural drainage systems. With modern urbanization, however, rivers and streams came to be treated primarily as elements to be controlled through technical solutions [9]. Gradually, they were straightened, channeled, and buried, becoming invisible infrastructure within the urban fabric and disappearing from the city's everyday landscape [10].

In the Brazilian context, this process has taken on particular significance in coastal cities, where urban expansion has often encroached on flood-prone areas and fragile water systems. The city of Vitória, capital of Espirito Santo, located in southeastern Brazil, is a striking example of this dynamic. Within its urban fabric, recurring flooding and its impacts on mobility and the use of public space have contributed to associating water with urban problems. This situation was particularly acute in areas originally prone to flooding, marked by the removal of mangroves, the filling in of waterways, and successive urban expansion projects throughout the 20th century [4, 10].

The Jucutuquara Administrative District, located in the southern part of the municipality (Fig. 1), fits directly into this context, having been built on a former floodplain whose natural water network has been progressively obscured.



Fig. 1. Global and regional location of the city of Vitoria, Brazil, with a focus on the region under analysis.

The Jucutuquara Stream has historically been one of the main structuring elements of this territory. With the expansion of the urban grid, its lower course was channeled, straightened, and subsequently covered, becoming part of the drainage infrastructure

associated with Paulino Muller Avenue. Although invisible in the current landscape, the stream continues to influence the hydrological behavior of the micro-basin. The flooding observed in the area appears to result from limitations in the drainage system, associated with the network's inability to handle intense rainfall events and the condition of the culverts.

Given this scenario, this article begins with the recognition that contemporary urban vulnerability stems both from the disappearance of water in urban areas and from the intensification of climate change, which has been increasing the frequency and severity of extreme precipitation events. The application of Nature-Based Solutions presents itself as a possible response to these problems [11, 12]. Thus, the objective of this study is to investigate the potential of Nature-Based Solutions and water-sensitive urban planning as climate adaptation strategies, applied to a proposed intervention on Paulino Muller Avenue in Vitoria, Brazil.

By proposing the partial renaturalization of the Jucutuquara Stream, the aim is to mitigate flooding associated with heavy rainfall in an impervious urban environment and to reestablish, albeit partially, the relationship between the city and water in the contemporary urban context, integrating river restoration, green and blue infrastructure, and urban resilience [14, 15].

2 Method

The study adopts a qualitative approach of an exploratory and design-oriented nature, combining historical analysis, spatial analysis, and the development of an urban proposal. The method is based on the understanding that the recurring flooding observed in the Jucutuquara Administrative Region is not solely the result of isolated failures in the drainage system or the occurrence of heavy rains, but rather a combination of critical hydrological events and historical urbanization processes that have led to the progressive obscuring of the natural water network [4, 10, 15].

The first stage consisted of a historical and cartographic analysis of the study area, based on old maps, aerial imagery, and documentary records, with the aim of understanding the evolution of the urban fabric and the gradual disappearance of watercourses. This analysis made it possible to identify the original course of the Jucutuquara Stream and its relationship with the former floodplain upon which the region was urbanized, highlighting the progressive overlap of urban infrastructure with the preexisting water system.

In the second phase, field inspections were conducted along Paulino Muller Avenue, including a survey of the road's physical and functional characteristics. Aspects such as the road cross-section, degree of imperviousness, sidewalk configuration, the presence of trees, the functioning of the surface drainage system, and recurring flooding points were observed. This stage provided insight into how the stream, although hidden, continues to influence water behavior in the area.

Figure 2 shows the location of the avenue within the urban context of the Jucutuquara Administrative Region (Fig. 2a), as well as an aerial view of a representative section of the road (Fig. 2b), with a graphic indication of the watercourse hidden beneath the culvert. Paulino Muller Avenue serves as the structural axis of the study area, and its

current road infrastructure overlaps the lower course of the stream. This relationship was fundamental to the next stage of the research, involving an analysis of the urban, morphological, and hydrological dynamics of the site.

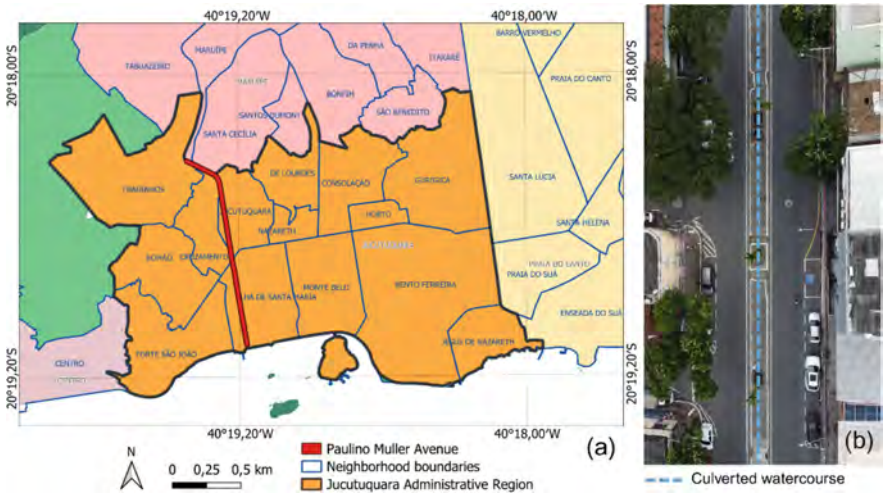


Fig. 2. Location of Paulino Muller Avenue within the urban context of the Jucutuquara Administrative Region.

The third stage consisted of conducting a comprehensive assessment, integrating historical, cartographic, and empirical data. The analysis highlighted the relationship between the channelization, straightening, and subsequent culverting of the lower course of the Jucutuquara Stream, urban soil sealing, and the overloading of the drainage system during heavy rainfall events. In the lower reaches of the micro-basin, this situation can be exacerbated by tidal levels, while in other areas, the maintenance and cleaning conditions of stormwater conduits also play a significant role.

Finally, a design study for urban intervention was developed, guided by the principles of Green and Blue Infrastructure, Sustainable Urban Drainage Systems (SUDS), Low Impact Development (LID), and Water Sensitive Urban Design (WSUD) approaches widely recognized in international literature as effective strategies for integrating natural hydrological processes into contemporary urban planning [3, 5, 16].

3 Results

The study's findings show that the vulnerability to flooding observed along Paulino Muller Avenue is directly linked to the historical process of the Jucutuquara Stream's disappearance. The channeling, straightening, and subsequent culverting of the stream's lower course, combined with the imperviousness of urban soil and the consolidation of the built environment, have compromised the natural capacity for retention, infiltration, and dissipation of stormwater [5, 17]. Although currently invisible in the urban landscape,

the stream remains hydrologically active and manifests itself through recurring flooding during heavy rainfall events. These episodes are related to the inadequacy of the drainage network, the maintenance conditions of the culverts, and, in the lower reaches of the micro-basin, also to the influence of the tide.

Paulino Muller Avenue is an arterial road located within a densely populated urban area, characterized by a historical lack of priority given to pedestrians, narrow sidewalks, continuous paving, and recurring conflicts between traffic, street furniture, and vegetation. At the same time, it has established itself as a key component of the road and drainage infrastructure associated with the lower course of the Jucutuquara Stream. However, the progressive disappearance of the natural water network has compromised not only the stream's environmental function but also its flood-mitigation capacity, making the avenue a critical axis in terms of urban drainage [6, 7].

In this context, the proposed intervention seeks to adapt green and blue infrastructure principles to the small scale of the avenue, balancing drainage, mobility, and the improvement of public space [14, 18]. Its central strategy consists of the partial daylighting and restoration of the Jucutuquara Stream along the median strip of the road, through the reopening of the currently hidden channel. The new channel bed is designed with a shallow depth, vegetated banks, and gentle slopes, allowing for increased hydraulic capacity, reduced flow velocity, and the promotion of natural stormwater dissipation processes. The stream, daylighted and restored along the central axis, is combined with a two-way bike path, widened sidewalks, and distributed drainage systems, resulting in a road improvement project compatible with the street's continued function as an arterial route.

Water management is now carried out in a distributed manner. Part of the surface runoff is directed to the daylighted channel, while linear rain gardens, installed alongside the sidewalks, receive additional volumes through regular openings in the curb. This strategy reduces the concentration of flows at specific points, extends the water retention time in the system, and promotes infiltration and evapotranspiration processes, helping to relieve the overload on the conventional drainage system, as widely discussed in the literature on SUDS, LID, and water-sensitive urban planning [3, 5, 16]. The proposal is presented for a typical section of Paulino Muller Avenue (Fig. 3).

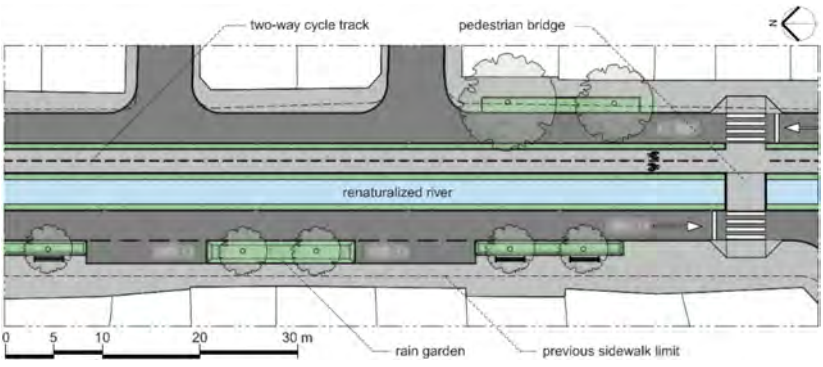


Fig. 3. Site plan for the proposed project on Paulino Muller Avenue.

The proposed project reorganizes the channel, which has been daylighted along its central axis, and distributes drainage and circulation systems along the sides. Close to the sidewalks, the rain gardens receive surface runoff through 0.50-m openings in the curb, spaced every 15 m. The section now operates with two directions of surface runoff: one toward the daylighted stream in the central axis and the other toward the rain gardens located at the curb level. This strategy distributes the runoff, reduces the concentrated load on a single point, and increases the hydraulic efficiency of the system. The adoption of continuous longitudinal plant beds also addresses local constraints, expanding the permeable areas and the volume of soil available to the roots of existing trees.

In addition to the hydrological benefits, the project promotes the enhancement of public space. The expansion of permeable areas and the increase in the amount of soil available for trees contribute to improved urban tree cover and the microclimate. The inclusion of a bike path integrated into the green-blue corridor reinforces the multifunctionality of the road, reconciling active mobility, sustainable drainage, and landscape enhancement without compromising existing road functionality, in line with contemporary approaches to green infrastructure and nature-based urban adaptation [3, 5, 7].

The spatial reorganization proposed in the project highlights the relationship between the daylighted channel, vehicular traffic, public spaces, tree planting, and distributed drainage systems incorporated along the road section (Fig. 4).

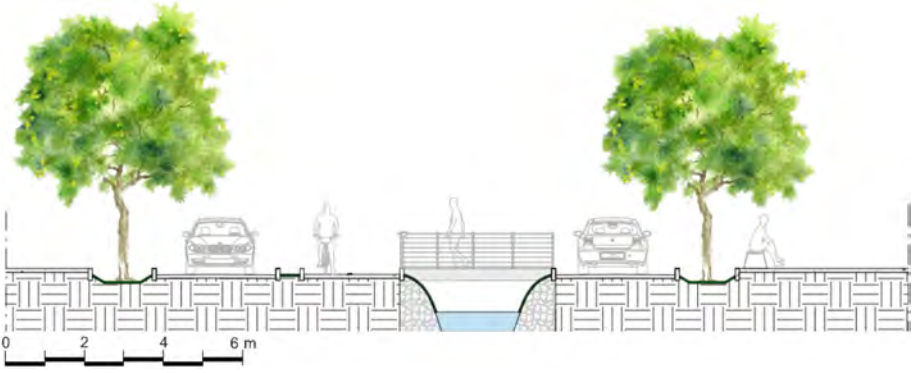


Fig. 4. Typical cross-section of Paulino Muller Avenue following the intervention.

The road section proposed reconciles the partial restoration of the water system with the maintenance of the avenue's urban functionality. The proposed road profile incorporates the reopening of the stream in a way that integrates it with the existing public space, without completely eliminating vehicular traffic but redefining its priorities in favor of an urban approach that is more sensitive to water.

Another important point revealed by the results is the feasibility of the proposal in an established urban context. Unlike the ideal situations often addressed in theoretical studies, Paulino Muller Avenue features buildings lining its entire length, a lack of significant setbacks, and a narrow roadway, which imposes significant spatial constraints

on the implementation of climate adaptation solutions. These conditions reflect the reality of most contemporary urban spaces.

The results nevertheless demonstrate that, even in the face of physical and morphological constraints, it is possible to integrate nature-based solutions into the existing urban fabric. The partial daylighting and restoration of the Jucutuquara Stream, combined with distributed drainage systems and the reorganization of the road section, demonstrates that smaller-scale interventions can yield significant gains in hydrological performance, public space quality, and urban climate resilience [2, 6].

4 Conclusions

In conclusion, based on the historical, diagnostic, and project analysis conducted in this study, it is evident that the recurring flooding observed in the Jucutuquara Administrative Region is deeply linked to the historical process of the disappearance of water in urban space. The channeling, straightening, and subsequent culverting of the lower course of the Jucutuquara Stream, combined with soil sealing and the prioritization of technical solutions focused on hydraulic control, have resulted in the loss of the territory's natural capacity to accommodate extreme hydrological events.

The proposal for the partial daylighting and restoration of the stream along Paulino Muller Avenue demonstrates that it is possible to reestablish, albeit partially, the relationship between the city and water systems in established urban contexts. By reintegrating the watercourse into the urban landscape through nature-based solutions and distributed drainage systems, the intervention can increase water retention capacity, reduce surface runoff, and contribute to flood mitigation. More than a technical solution, the proposal points to a possible paradigm shift in urban planning, recognizing water not merely as an element to be controlled, but as a structuring component of urban space. Although applied to a specific case study, the methodology and guidelines presented can be adapted to other urban contexts facing similar challenges in the face of climate change, as noted in the reviewed literature [1, 3, 12].

The incorporation of water-sensitive approaches into urban planning is a key pathway to building more resilient coastal cities that can coexist with the natural dynamics of water and respond more adaptively to the impacts of climate change. At the same time, the study underscores the importance of reintegrating water into the urban landscape as an active element of the territorial structure and the enhancement of public spaces.

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Microclimatic Assessment of Tree Planting Scenarios as a Nature-Based Cooling Solution in Two Urban Districts of Athens, Greece

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Abstract. Climate change is expected to intensify heat stress in the following years, especially in Mediterranean cities. This paper assesses the microclimatic conditions prevailing in two urban districts of Athens under different climate change scenarios and evaluates the effects of street trees as a nature-based solution. Two study areas, representing Local Climate Zones LCZ2 and LCZ3, are modelled with ENVI-met V5 under three time periods, historical baseline (1980–2000) and two future periods (2040–2060 and 2080–2099) and in view of two climate change scenarios, RCP 4.5 and RCP 8.5. Climate data derived from dynamically downscaling high-resolution RegCM4 outputs for both LCZ areas. Typical winter and summer days are simulated and air temperature (Tair) is studied on the pedestrian level. Both LCZs show significant warming, with RCP 8.5 being the most critical scenario and Tair rising by up to 4.5 °C, during summer midday, towards the end of the century. As a subsequent step, tree planting scenarios, derived from urban geometry, shading and sidewalk constraints, were tested. The densest tree pattern results in mean Tair reduction by up to 0.79 °C. The study suggests that morphology-based street greening in different LCZ typologies can alleviate future heat stress and reduce thermal peaks in summer to support climate-resilient design in dense Mediterranean urban districts.

Keywords: Urban microclimate · Local Climate Zones · ENVI-met · Street trees · Climate change adaptation

1 Introduction

Mediterranean cities are expected to experience more frequent and intense heat stress as climate change progresses. Dense building patterns, hardscape materials and minimum vegetation strengthen urban overheating and worsen pedestrian thermal conditions. Street trees are among the most studied nature-based solutions for urban cooling because they combine direct shading with evapotranspiration and can be integrated in existing streetscapes [1, 2]. In Athens, field measurements have already shown that tree-shaded streets can moderate air temperature during very hot periods by up to 2.2 °C [3].

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The cooling effectiveness of trees, however, is strongly influenced by urban form. Street orientation, aspect ratio, sky-view factor, albedo, planting continuity and species characteristics all influence cooling intensity and spatial distribution. Previous studies have shown that the same tree type may perform very differently depending on canyon depth, solar exposure and the arrangement of adjacent buildings [4–6]. This makes morphology-sensitive design especially important in compact districts, where sidewalks, parking, balcony overhangs and underground infrastructure constrain planting opportunities.

At the same time, urban greening strategies need to be tested under future climate conditions and bridge climate-change projections and realistic, geometry-driven planting scenarios in Mediterranean districts with limited space. Microclimate simulation tools such as ENVI-met allow detailed analysis of atmosphere-surface-vegetation interactions at street level and are widely used for testing vegetation strategies in complex urban settings while incorporating detailed climate data [7–10].

Against this background, the present paper examines two urban districts of Athens, Greece, representing LCZ2 (compact mid-rise) and LCZ3 (compact low-rise). The study first quantifies current and future warming under two Representative Concentration Pathways (RCP 4.5 and RCP 8.5) and then evaluates two street-tree planting scenarios derived from geometric and functional constraints. The goal is to identify the most critical future case and assess how much morphology-based tree planting can reduce air temperature at pedestrian level.

2 Materials and Methods

2.1 Study Areas

The study areas are located in the city of Athens, Greece, with a Mediterranean climate (Köppen climate classification: Csa), characterized by hot, dry summers, mild and wet winters [11]. The selection of the areas was made on the basis of the Local Climate Zones (LCZ) classification of Agathangelidis et al. [12]. The first area is located in the city center and represents LCZ2, a compact mid-rise fabric with deep canyons, high built density and very limited planting opportunities. The second is located in Nikaia and represents LCZ3, a lower-rise but still dense district with wider sidewalks and greater capacity for continuous tree cover. Both areas were standardized to the same plan dimensions (200x150m) to support direct comparison, while preserving their dominant morphological characteristics, street orientations and existing vegetation patterns. The location, boundaries and main characteristics of the areas are included in Table 1 and Figs. 1 and 2.

Table 1. Main characteristics of the two case study areas.

Parameters	LCZ2	LCZ3
Geographic Location	37.961923, 23.731105	37.968133, 23.645241
Urban typology	Compact mid-rise	Compact low-rise
Area	30,000 m^2	30,000 m^2
Building coverage ratio	56.36%	57.21%
Average street-canyon H/W ratio	1.76	0.94
Typical sidewalk width	0.5–1.2 m	1.0–3.0 m
Tree density	10.3 trees/ha	55 trees/ha



Fig. 1. LCZ2, Athens



Fig. 2. LCZ3, Nikaia

2.2 Definition of Climate Scenarios and Model Set up

The two districts were modelled in ENVI-met V5, a three-dimensional non-hydrostatic model for surface-plant-air interactions. For each case, the ENVI-met simulation represented one full typical meteorological day (24 h). Climate boundary conditions were derived from dynamically downscaled regional climate-model output based on RegCM4 for one historical period (1980–2000) and two future periods (2040–2060 and 2080–2099), under RCP 4.5 and RCP 8.5 [13, 14]. The meteorological parameters were issued at 3-h temporal resolution and were averaged over each 20-year period in order to produce typical winter and summer weather files representative of January and July conditions. The data include air temperature (Tair, °C), relative humidity (RH, %) and wind speed (WS, m/s). The 3-h data were then linearly interpolated in 24-h time series and were incorporated within the ENVI-met model through simple forcing option.

For setting up the area in the three-dimensional space of ENVI-met, the basic morphological parameters were defined. Each model covered a standardized domain of 150 × 200 × 60 m using a 60 × 80 × 20 grid with cell dimensions of 2.5 × 2.5 × 3 m. Six nesting grids were added around the main domain to reduce boundary effects. Simulations ran for 24 h with hourly outputs. The physical properties of the materials and the assigned construction profiles reflect the construction period of the buildings, mostly dated before 1980. Finally, *Citrus aurantium* (bitter orange) evergreen tree species was selected as the main tree type for both study areas with LAD value of 2 m^2/m^3.

2.3 Design of Planting Scenarios

Planting scenarios were developed from a combination of the areas' geometry, solar exposure, pedestrian movement and tree characteristics. The selected tree species were Citrus sp., Magnolia sp., Tilia sp. and Nerium oleander. The proposed layouts accounted for legislative requirements, geometric constraints of built environment and tree species characteristics. Species selection followed urban-resilience and geometric criteria. Citrus sp. was used as the smallest tree option for narrow streets, Magnolia sp. and Tilia sp. for wider sections, and Nerium oleander as a secondary shrub layer where sufficient space existed. Practical concerns such as drought tolerance, canopy size and conflict with pavement and building elements were also considered [15].

Two planting scenarios were evaluated in each district. Intermediate Scenario A of moderate intervention (Figs. 3a and 4a) and the final feasible Scenario B (Figs. 3b and 4b) which represents the densest feasible pattern under the same geometric constraints. The same ENVI-met settings used for the climate-change assessment were retained for the NBS simulations, so that the effects of vegetation could be isolated more clearly.

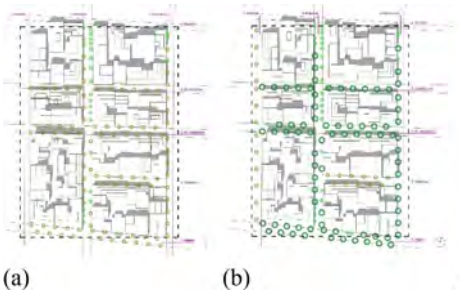


Fig. 3. Scenario A (a) and B (b), LCZ2, Athens

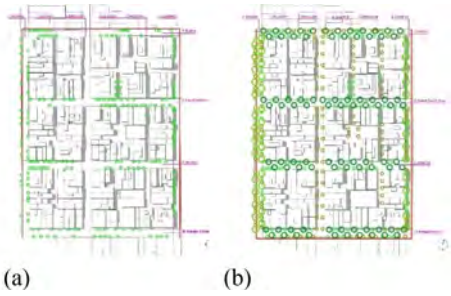


Fig. 4. Scenario A (a) and B (b), LCZ3, Nikaia

3 Results

3.1 Future Warming and Identification of the Most Critical Scenario

The following analysis focuses on air temperature results at 12:00 local time, which was selected as the critical midday time step due to increased solar exposure and thermal stress. The two LCZs show progressive warming during both time periods (2040–2060 and 2080–2099) and under both RCP scenarios (RCP 4.5 and RCP 8.5) (Figs. 5, 6, 7, and 8). By mid-century, the average temperature increased similarly for both RCP 4.5 and RCP 8.5 scenarios. Towards the end of the century, RCP 4.5 stabilizes while RCP 8.5 climaxes reaching peak warming, making it the most critical scenario. In detail, for LCZ2, for the summer period, the average temperature for the historical period (1980–2000) was 30.67 °C. By mid-century, the average temperature increased similarly for both RCP 4.5 and RCP 8.5 scenarios (9.10% and 7.39% respectively). At the end of the century, RCP 4.5 stabilizes whereas in the case of RCP 8.5 the increase climaxed

reaching nearly 14.4% (4.41 °C over historical baseline). For the winter period, the absolute temperature increase is lower than summer but follows similar trends. The increase for both scenarios for mid-century is +1.62 °C (15.4%) with RCP 4.5 and RCP 8.5 showing nearly identical warming. Towards the end of the century, however, the rise under RCP 8.5 intensifies to +3.37 °C (31.97%) above the reference period, while RCP 4.5 stabilizes at +2.04 °C (19.4%).

For LCZ3 area, the average temperature for 1980–2000, for a typical summer day of July was 28.39 °C. Towards mid-century both RCP 4.5 and RCP 8.5 suggest an increase of air temperature by 9.01% and 8.42%, respectively, showcasing a similar warming trend. By the end of the century RCP 4.5 steadily stabilizes with an increase of 10.26% compared to the historical baseline value whereas in the case of RCP 8.5 the rise increases by 15.88%. For a typical winter day in January, compared to the historical period, average air temperature value of 11.80 °C, throughout mid-century both case scenarios increase between +1.72 °C (RCP 4.5, +14.6%) to 1.73 °C (RCP 8.5, +14.7%). The highest difference is again observed at the end of the century where RCP 4.5 increase balances at +2.15 °C (+18.2%) compared to RCP 8.5 that intensifies reaching a + 3.46 °C (+29.32%) rise compared to historical state.

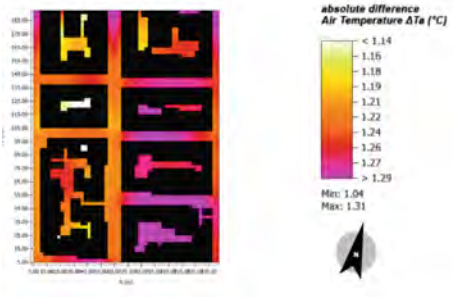


Fig. 5. LCZ2, Jan, RCP 8.5 vs. RCP 4.5, 12:00

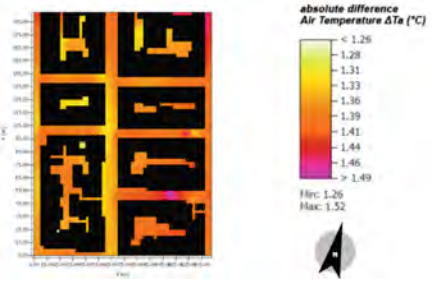


Fig. 6. LCZ2, Jul, RCP 8.5 vs. RCP 4.5, 12:00

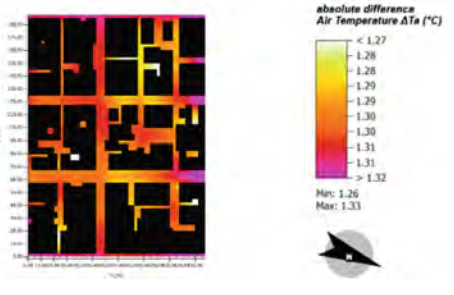


Fig. 7. LCZ3, Jan, RCP 8.5 vs. RCP 4.5, 12:00

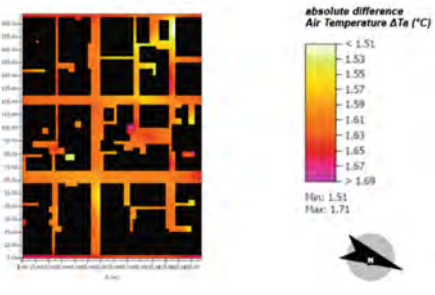


Fig. 8. LCZ3, Jul, RCP 8.5 vs. RCP 4.5, 12:00

3.2 Cooling Performance of Tree Planting Scenarios

During the most critical climate case (RCP 8.5, 2080–2099), denser tree planting configuration, Scenario B, consistently outperforms Scenario A for both areas under summer and winter midday conditions. The higher Tair reductions in air temperature are observed in LCZ3 (Table 2, Figs. 9 and 10). During summer, in LCZ2, mean Tair decreases from 35.08 °C under initial state to 35.04 °C in Scenario A and further to 34.84 °C in Scenario B. The decrease in average Tair is subtle with a reduction of −0.04 °C for A and −0.24 °C for B. The change is more pronounced in the maximum values with the hottest grid cells falling from 37.66 °C to 36.76–36.70 °C, and the Tair range decreasing from 6.29 °C to roughly 4.36 °C. Tree planting scenarios reduce midday thermal peaks, with the denser scenario B extending the effect spatially, resulting in a smoother and slightly cooler air temperature.

In LCZ3, Nikaia mean Tair during summer falls from 32.90 °C (baseline state) to 32.42 °C in Scenario A and 32.11 °C in Scenario B. The maximum drops from 35.48 °C to 34.14 °C with A and to 33.49 °C with B, and the range decreases from 4.79 °C to 2.79 °C (scenario A) and then 2.37 °C (scenario B). As a result, Tair fluctuations decrease, transitioning to a cooler and more uniform spatial state, that eliminates extremely hot peaks.

Table 2. Air temperature, July 12:00, RCP 8.5, 2080–2099.

Scenario	Area	Average Tair (°C)	Min Tair (°C)	Max Tair (°C)
Baseline	LCZ2	35.08	31.37	37.66
A	LCZ2	35.04 (−0.04)	32.42 (+1.05)	36.76 (−0.90)
B	LCZ2	34.84 (−0.24)	32.34 (+0.97)	36.70 (−0.96)
Baseline	LCZ3	32.90	30.69	35.48
A	LCZ3	32.42 (−0.48)	31.34 (+0.65)	34.14 (−1.34)
B	LCZ3	32.11 (−0.79)	31.12 (+0.43)	33.49 (−1.99)

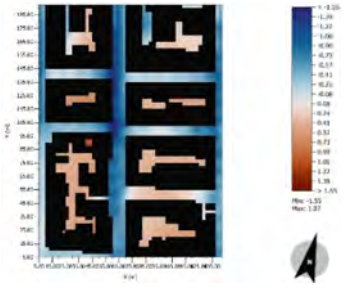


Fig. 9. LCZ2, RCP 8.5, 2080–99, Jul, 12:00, Scen. B – Ref., Air Temp., ΔTa (°C)

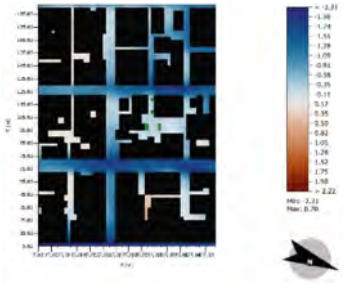


Fig. 10. LCZ3, RCP 8.5, 2080–99, Jul, 12:00, Scen. B – Ref., Air Temp., ΔTa (°C)

During winter, trees manage to produce only a slight cooling effect, suggesting that the proposed interventions do not create extreme cold conditions in the area. In the case of LCZ2, under the most beneficial planting scenario B, air temperature shows almost no change, with the average decreasing from 13.91 °C to 13.85 °C (−0.06 °C), and the range tightening marginally from 1.18 °C to 1.13 °C. This indicates that the air remains essentially stable in terms of comfort. In LCZ3, Nikaia, air temperature cools by −0.30 °C on average (15.29 °C to 14.99 °C), with a slight drop in the maximum value (16.02 °C to 15.64 °C) and a modest range compression (0.92 °C to 0.90 °C).

4 Discussion

The initial areas' state shows the strong influence of urban morphology on local air temperature. In winter at midday, LCZ3 is slightly warmer than LCZ2 (15.29 °C vs. 13.91 °C), due to lower buildings and wider streets that allow greater winter solar access. In summer, the pattern reverses: LCZ2 is warmer than LCZ3 (35.08 °C vs. 32.90 °C), reflecting its denser urban form, narrower canyons and lower vegetation cover. Under the critical scenario RCP 8.5, during summer, the denser planting layout (Scenario B) improves Tair in both districts, but with different magnitudes. In LCZ2, mean Tair decreases by −0.24 °C and the hottest locations by −0.96 °C whereas in LCZ3 the corresponding reductions are stronger; mean Tair is reduced by −0.79 °C and maximum reduction reaches −1.99 °C at peak locations. LCZ3 showcases greater benefits since its geometry allows wider and more continuous tree canopy development.

Planting also manages to reduce the spatial range between minimum and maximum Tair values. In LCZ2, the range decreases from 6.29 °C to 4.36 °C, while in LCZ3 it decreases from 4.79 °C to 2.37 °C. This indicates a more homogeneous thermal load across the study areas and a reduction of local overheating extremes. The strongest local reductions occur below and around the trees, where shading is most effective. In winter, the effect of planting on Tair remains limited, with mean changes of only −0.06 °C in LCZ2 and −0.30 °C in LCZ3. Overall, the winter outcomes reveal only a slight reduction in air temperature. This suggests that the proposed planting strategies provide summer benefits without causing pronounced winter cooling.

5 Conclusions

This study investigated how future climate conditions may affect the microclimate of two urban districts in Athens representing LCZ2 and LCZ3 and assessed the extent to which morphology-based street-tree planting can mitigate these impacts. The main outcome suggests that:

- Climate change is expected to intensify overheating in both areas, with the end-of-century RCP 8.5 state being the most critical.
- Planting scenarios manage to moderate future warming, reducing peak air temperatures by up to 1.99 °C, while causing only limited winter penalty.
- More open urban fabric of LCZ3 results in stronger summer cooling benefits by allowing denser tree planting layouts.

As part of the Re.Nature Cities research project, this work aims to quantify the effect of green intervention in cities and to understand how realistic street-greening strategies can support urban climate resilience in Athens and other dense Mediterranean cities, while also offering a basis for further investigation of extreme weather cases, additional urban typologies, and long-term adaptation pathways.

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Combined Seismic and Energy Retrofitting of Existing Reinforced Concrete Buildings Using Representative Retrofit Measures

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Abstract. In this paper, the main objective is the presentation of an approach for the integrated seismic and energy retrofitting of existing buildings in Greece, aiming at the establishment of optimal intervention strategies that enhance both structural and energy performance. The study focuses on representative buildings constructed in different periods, with different functions and structural typologies. A typical methodology is adopted, combining numerical simulations, analytical assessments and performance-based evaluation criteria. Various thermal insulation materials applied to the building envelope are examined to evaluate their effect on energy consumption, while alternative seismic retrofitting solutions, using different strengthening materials and techniques, are applied to assess their influence on seismic behavior. All analyses are conducted using software tools and comply with national codes and European standards. The comparative evaluation of results identifies retrofit solutions that achieve optimal seismic performance and improved energy efficiency, providing a framework for selecting technically viable and compliant strategies.

Keywords: Combined retrofitting · Energy retrofitting · Reinforced concrete buildings · Seismic upgrading · Thermal insulation materials (envelope)

1 Introduction

Residential buildings constitute the dominant share of the European building stock, accounting for approximately 75% of the total constructions. Many were built before modern seismic design codes and energy performance requirements, with about 40% before the 1960s, 45% during 1961–1990, and only 15% after 1991, with similar trends in southern Europe [1, 2]. As a result, many buildings do not comply with current seismic codes or energy regulations (EPBD), showing both seismic vulnerability and poor energy performance. In seismically active regions, this may lead to significant economic losses and fatalities, making integrated upgrading a crucial socio-economic priority.

In previous years, upgrading of existing buildings has mainly been addressed through independent approaches, focusing either on seismic strengthening or energy retrofitting.

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Seismic retrofitting strategies, including reinforced concrete jackets, steel bracing systems, fiber reinforced polymers (FRP), textile reinforced mortars (TRM) and base isolation systems, have been widely implemented to enhance structural capacity, ductility and overall performance, especially in high seismic hazard regions [3]. However, such approaches neglect the energy performance of the building envelope, limiting the potential for holistic improvements.

Energy retrofitting has been widely promoted across Europe due to environmental concerns and policies aiming to reduce greenhouse gas emissions and energy consumption in buildings. Typical measures include thermal insulation of the building envelope, window replacement, HVAC upgrades and integration of renewable energy technologies [1, 4], improving indoor comfort and reducing energy demand. However, such interventions are usually implemented independently of structural assessments, which is a major drawback in high seismic risk areas where structural deficiencies may remain unresolved.

1.1 Aim of the Study and Examined Scenarios

In recent years, the idea of combined seismic and energy retrofitting has attracted increasing interest as an efficient and sustainable approach for upgrading existing buildings, addressing structural safety and energy performance through joint interventions that optimize both technical effectiveness and economic feasibility [e.g. 2, 5–8]. Representative systems include multifunctional solutions, such as exoskeletons and energy-efficient facades with structural contribution, which can reduce overall costs, construction time and disruption to occupants while maximizing retrofit benefits [5, 6, 8].

The importance of such approaches is further supported by European policies, including the Green Deal and the Renovation Wave Strategy, which promote large-scale energy renovation while ensuring resilience [4]. At the same time, seismic risk remains critical in southern Europe, particularly in Greece, where a large portion of the building stock was constructed before modern seismic codes and exhibits low energy performance [9].

However, despite this growing interest, there is still a lack of standardized methodologies applicable to different building typologies and seismic zones, as most studies focus on isolated cases rather than comprehensive building stock approaches.

In this study, the term “optimal retrofit strategy” used as a reference to interventions that simultaneously improve structural safety and energy efficiency through integrated and compatible solutions applied on the building envelope. The assessment combines seismic indicators, such as base shear capacity and deformation demand, with energy ones related to annual heating and cooling demand reduction.

In this framework, the present study aims to develop and apply a method for the integrated seismic and energy retrofitting on existing residential buildings in Greece through the combination of externally applied thermal insulation plates with TRM. The proposed scheme is applied to four multi-family buildings constructed in different time periods (Case Study 1–1969, Case Study 2–1976, Case Study 3–1985, Case Study 4–1998) and located in distinct seismic and climatic zones, allowing to have a comprehensive assessment of its applicability.

The typical floor plan of each building is presented in Fig. 1. The total floor area per floor for each case study accordingly is: 161.74 m^2 (5 floors), 345.61 m^2 (5 floors) + 318.15 m^2, 164.74 m^2 (4 floors) and 200.28 m^2 (6 floors).

The methodology combines structural analysis and energy performance assessment within an integrated evaluation framework, followed by the implementation of optimized retrofit solutions with dual functionality, aiming to simultaneously improve both seismic and energy performance.

In a subsequent stage of the present research, a methodology is being developed for the analytical quantification of the stiffness and strength increase provided by the proposed combined seismic and energy retrofit system on infilled reinforced concrete frames at a global building level. The objective is to establish simplified yet reliable analytical expressions that can support the practical implementation and wider applicability of integrated retrofit strategies in existing building stock.

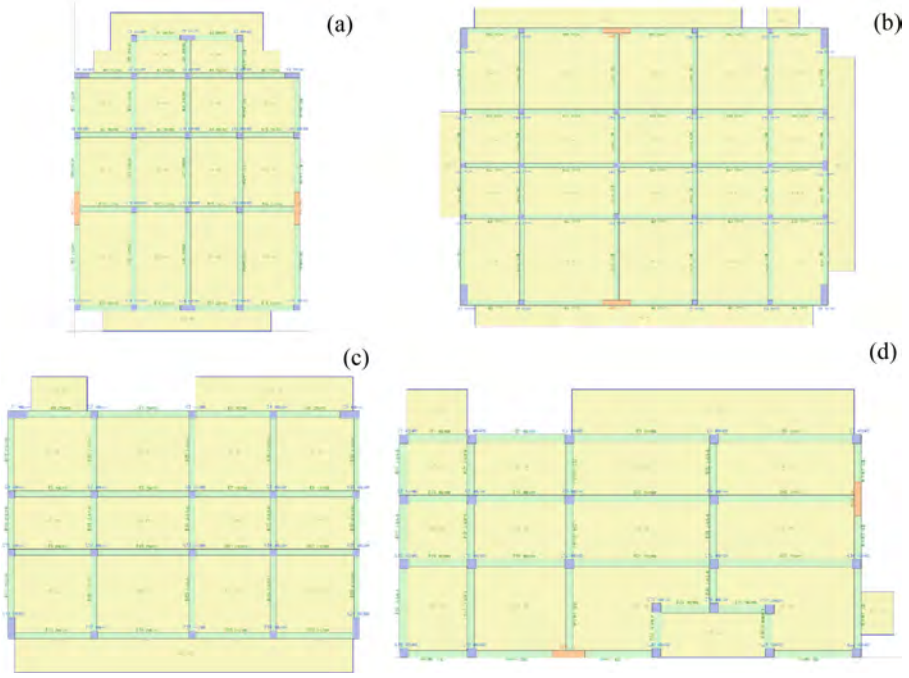


Fig. 1. Typical floor plans of the examined buildings: (a) Case study 1 (5 storeys); (b) Case study 2 (5 storeys); (c) Case study 3 (4 storeys); (d) Case study 4 (6 storeys).

2 Energy Performance Assessment & Upgrading

Dynamic simulations using the software EnergyPlus were conducted to evaluate the energy performance of the case studies. Detailed numerical models were developed for each building, considering their geometric characteristics, construction materials, thermal properties and operational conditions, in order to determine the energy performance

for the existing condition. The building envelope characteristics, occupancy schedules and thermostat settings were defined in accordance with the Technical Guidelines of KENAK (TOTEE 1 & 2).

External thermal insulation systems were then applied to the building envelope, considering expanded polystyrene (EPS – 25 kg/m^3) and extruded polystyrene (XPS – 35 kg/m^3), with insulation thickness derived from analytical calculations in line with the Greek National Annex. All retrofitting scenarios were evaluated under the same conditions, enabling direct comparison with the baseline case, focusing primarily on annual heating and cooling energy demand.

The application of external thermal insulation systems using EPS and XPS significantly improved the energy performance of all examined buildings. Heating demand reductions ranged between approximately 88–93%, while cooling demand reductions varied between 19–32%, depending on the climatic conditions and building characteristics of each case study. The comparative results of the results of the energy simulations for all case studies are presented in Fig. 2.

The highest reductions in heating demand were observed in colder climatic regions, where heat losses through the building envelope are more critical, while cooling demand reductions became more significant in warmer areas. In all examined cases, the difference between EPS and XPS remained relatively limited, indicating comparable thermal performance and suggesting that the final selection between the two materials may mainly depend on practical, economic or construction related criteria without considering the thermal contribution. The climatic differences between the examined regions are illustrated in Fig. 3 through the air dry-bulb temperature profiles for each case.

Overall, the results demonstrate that external thermal insulation systems can substantially improve the energy efficiency of existing reinforced concrete buildings regardless of construction period or structural typology.

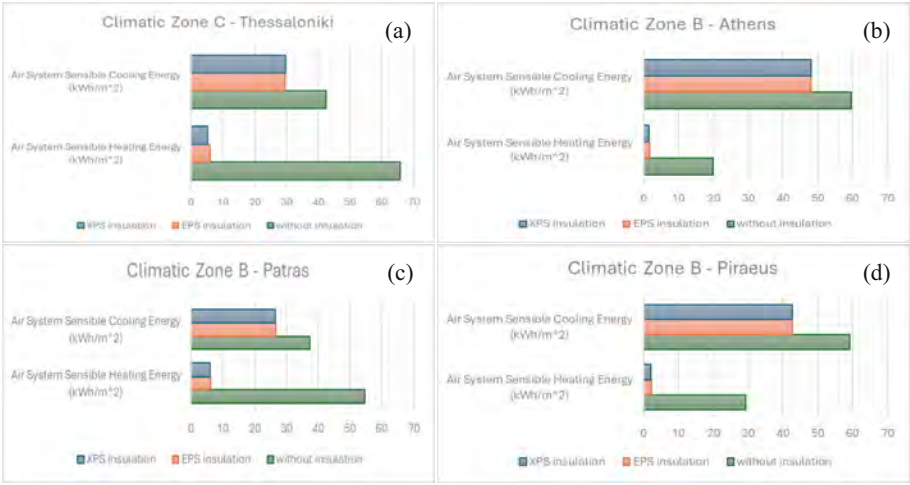


Fig. 2. Bar chart with the results of the energy simulation of: (a) CS1 (Thessaloniki), (b) CS2 (Athens), (c) CS3 (Patras), (d) CS4 (Piraeus).

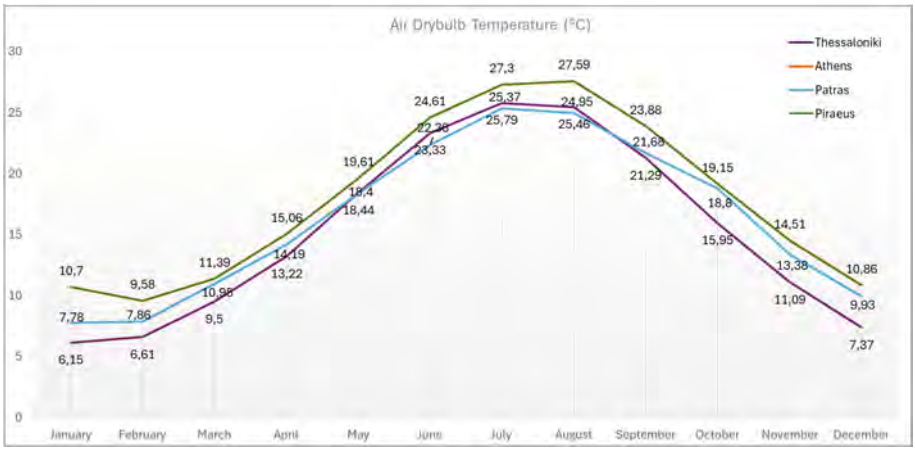


Fig. 3. Air Drybulb Temperature (^{O}C) of each region (Thessaloniki, Athens, Patras, Piraeus).

3 Seismic Simulations and Strengthening

Numerical models were developed for each case study using SeismoBuild to perform the seismic assessment of the examined buildings. Each building was initially analyzed in its existing condition through nonlinear static (pushover) analysis to evaluate its seismic capacity and identify structural weaknesses.

Seismic strengthening interventions were then applied based on the structural characteristics, construction period and seismic zone, including reinforced concrete shear walls, reinforced concrete jacketing, carbon fiber-reinforced polymers (CFRP) and glass-based textile reinforced mortars (TRM). TRMs were modeled using equivalent diagonal cross-bracing elements with hinged connections.

A comparison between initial and strengthened conditions was made to evaluate the effectiveness of each intervention. All analyses were conducted for the Significant Damage (SD) Limit State.

3.1 Case Studies

The *first case study* (Seismic Zone ZI) revealed limited structural capacity, with a maximum base shear of approximately 2,090 kN and a fundamental period of 0.709 s, indicating relatively low stiffness and increased deformation demand. The initial structural response was mainly governed by brittle shear mechanisms concentrated in the lower storeys. Strengthening with FRP and TRM improved the seismic response, increasing the base shear capacity to approximately 2,395 kN (≈15%) while reducing the fundamental period to 0.624 s.

The *second case study* (Seismic Zone ZI), characterized by vertical irregularity, exhibited moderate strength but limited deformation capacity, with an initial base shear of approximately 3,110 kN and a period of 0.732 s. Brittle shear failures were mainly

concentrated in the lower storeys. The retrofit strategy including FRP, TRM and hidden columns significantly improved the structural response, increasing the base shear capacity to approximately 3,870 kN (≈24%) and reducing the fundamental period to 0.652 s.

The *third case study*, constructed in 1985 and located in Seismic Zone II, consisted of a reinforced concrete frame system without shear walls, resulting in a relatively flexible structural response. The initial response showed combined flexural and shear failure mechanisms, with shear failures dominating in lower-storey columns. Strengthening with FRP and TRM increased the base shear capacity from approximately 2,275 kN to 2,695 kN (≈19%), while the retrofit improved the overall seismic response, although the structure remained relatively flexible.

The *fourth case study*, irregular in plan and located in Seismic Zone I, exhibited relatively high initial strength but also significant deformation demand. Damage was concentrated mainly in the lower storeys, with both shear and chord rotation failure mechanisms observed. The retrofit strategy, including RC jackets, new shear walls, FRP and TRM, significantly improved the structural response, increasing the base shear capacity from approximately 4,100 kN to 7,800 kN (≈90%) and reducing the fundamental period from 0.633 s to 0.564 s.

4 Integrated Evaluation of Retrofit Effectiveness

The combined evaluation of seismic and energy performance demonstrates that integrated retrofit strategies applied through the building envelope can provide substantial improvements in both structural safety and energy efficiency. The proposed interventions achieved significant reductions in energy demand together with increased lateral resistance and improved overall seismic behavior.

In addition, the use of multifunctional retrofit systems contributes to reduced construction complexity and minimized intervention requirements, supporting more sustainable and resource-efficient renovation practices for the existing building stock. A comparative summary of the integrated seismic and energy retrofit performance for all case studies is presented in Table 1.

Table 1. Integrated evaluation of seismic and energy retrofit performance.

Case Study	Heating Demand Reduction (%)	Cooling Demand Reduction (%)	Base Shear (kN) (Before → After)	Fundamental Period (s) (Before → After)	Main Retrofit Measures
CS1	≈92	≈30–32	2,090 → 2,395 (+15%)	0.709 → 0.624	TRM + FRP + ETICS
CS2	≈92	≈19	3,110 → 3,870 (+24%)	0.732 → 0.652	TRM + FRP + hidden columns + ETICS

(*continued*)

Table 1. (*continued*)

Case Study	Heating Demand Reduction (%)	Cooling Demand Reduction (%)	Base Shear (kN) (Before → After)	Fundamental Period (s) (Before → After)	Main Retrofit Measures
CS3	≈88–89	≈28–30	2,275 → 2,695 (+19%)	0.505 → 0.515	TRM + FRP + ETICS
CS4	≈92–93	≈27–28	4,100 → 7,800 (+90%)	0.633 → 0.564	RC jackets + shear walls + TRM + FRP + ETICS

Case Study	Overall Seismic Response
CS1	Increased stiffness and reduced deformation demand
CS2	Improved lateral resistance and stability
CS3	Increased strength with limited stiffness improvement
CS4	Significant improvement in strength and stiffness

5 Limitations and Future Work

The present study is limited to nonlinear static analyses and does not include nonlinear dynamic simulations or detailed lifecycle and economic assessment. Furthermore, the examined case studies, although representative of the Greek building stock, remain limited in number. Future research should focus on performance-based optimization approaches integrating environmental, economic and resilience-related indicators.

6 Conclusions

The results indicate that the examined buildings – representative of different construction periods - are highly affected by both seismic vulnerability and poor energy performance, although the dominant issues vary depending on construction period, structural configuration and location. Older buildings and frame-dominated systems, particularly those without shear walls, exhibit higher deformation demands and increased shear-related damage, leading to reduced seismic performance. In contrast, buildings with stiffer systems or enhanced with additional lateral load-resisting elements show clear improvements in strength, stiffness and overall seismic performance. The influence of the seismic zone is also evident, as buildings in more demanding zones require stronger retrofit schemes. From an energy perspective, external thermal insulation proves highly effective across all cases, significantly reducing heating demand, while cooling demand is reduced to a lesser extent. The benefits are more pronounced in colder regions, whereas in warmer areas the response is more balanced. Differences between EPS and XPS remain minimal, indicating comparable effectiveness.

Overall, the proposed integrated retrofit strategy demonstrates that combined seismic and energy interventions applied through the building envelope can significantly improve both structural safety and energy efficiency. At the same time, the proposed approach supports circular economy principles by extending the service life of existing buildings, reducing intervention redundancy and promoting multifunctional retrofit solutions with lower overall environmental and construction impact. This finding is consistent with the existing literature, where integrated seismic and energy retrofitting strategies are recognized as more efficient compared to uncoupled interventions, offering improved overall performance and cost-effectiveness [6]. In the case of the Greek building stock and European building stock with similar characteristics, such combined solutions can be considered not only advantageous but also a necessary pathway, as they enable the simultaneous improvement of structural safety and energy efficiency through interventions on the building envelope.

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Assessing Climate Resilience in Informal Settlements of the Global South: Evidence from Mbabane, Eswatini

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Abstract. Informal settlements in the Global South are highly vulnerable to climate-related hazards due to inadequate infrastructure, environmental exposure and limited adaptive capacity. However, existing urban resilience assessment frameworks predominantly focus on formal urban systems and have seen limited practical application within informal settlement contexts. As a result, climate vulnerabilities and adaptive capacity within these areas remain insufficiently diagnosed, limiting evidence-based climate responsive upgrading interventions. To address this limitation, the authors previously developed the Resilience Assessment Framework for Informal Settlements (RAFIS), grounded in the resilience attributes of diversity, redundancy, modularity, and connectivity. While RAFIS established a context-sensitive framework for resilience assessment in informal settlements, its empirical operationalisation within a real settlement context remained unexplored. This paper applies RAFIS in Msunduza informal settlement, Mbabane, Eswatini, to demonstrate a transferable approach for assessing climate vulnerabilities and adaptive capacity in informal settlements within similar contexts. A mixed-method case study approach was employed using document analysis, expert interviews, and structured mapping to apply the framework. Data was collected from 230 residential buildings and settlement infrastructure systems using Epicollect5 and analysed using QGIS and SPSS. The findings revealed low adaptive capacity associated with inadequate drainage systems, limited backup water and energy systems, fragmented infrastructure connectivity, and poor thermal performance of buildings. The study demonstrates how resilience attributes can be translated into measurable indicators that help identify vulnerabilities and inform evidence-based climate-responsive upgrading interventions in informal settlements of the Global South.

Keywords: Informal Settlements · Climate Resilience · Vulnerability Assessment · Climate Adaptation · Climate-responsive Upgrading

1 Introduction

Informal settlements constitute a significant proportion of urban growth in the Global South and are among the urban areas most vulnerable to climate-related hazards [1, 2]. Urban resilience assessment frameworks have increasingly been developed to support

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climate adaptation planning. However, they predominantly focus on formal urban systems, and their practical application within informal settlement contexts is limited [3, 4]. As a result, climate vulnerabilities and adaptive capacity within informal settlements remain insufficiently diagnosed, limiting the ability to support evidence-based upgrading interventions.

To address the limited contextual applicability of existing frameworks, the authors previously developed the Resilience Assessment Framework for Informal Settlements (RAFIS), grounded in the resilience attributes of diversity, redundancy, modularity, and connectivity [5]. This paper tests RAFIS in Msunduza informal settlement, Mbabane, Eswatini, to demonstrate a transferable approach for assessing climate vulnerabilities and adaptive capacity in informal settlements within similar Global South contexts.

2 Literature Review

2.1 Climate Resilience in Informal Settlements

Informal settlements are increasingly recognized as some of the most climate-vulnerable urban environments due to limited infrastructure and access to basic services, poor housing conditions, and environmental exposure, [2]. Climate-related hazards such as extreme heat and intense rainfall disproportionately affect informal settlements because of their location in environmentally sensitive areas and their limited adaptive capacity [6].

Urban resilience has emerged as an important concept for understanding how urban systems respond, adapt, and recover from environmental disturbances [7, 8]. Within resilience-informed built environment research, diversity, redundancy, modularity, and connectivity are recognised as key attributes supporting urban adaptive capacity [9].

Diversity enables flexibility through the availability of multiple systems and resources, redundancy supports continued functioning during disruptions through backup systems, connectivity supports infrastructure integration and accessibility, while modularity enables subsystems to function independently during disturbances [8, 10]). The absence or weakness of these attributes may therefore indicate reduced adaptive capacity and increased climate vulnerability within informal settlements.

2.2 Resilience Assessment Frameworks and Informal Settlements

Several urban resilience assessment frameworks and tools have been developed to support climate adaptation planning and resilience evaluation [3, 11]. However, many of these frameworks have limited applicability within informal settlements, where spatial informality, infrastructural fragmentation, and environmental vulnerability require context-sensitive assessment approaches [4]. Existing resilience assessment frameworks such as the City Resilience Index, City Resilience Profiling Tool, Disaster Resilience Scorecard for Cities, and City Resilience Action Planning Tool, often rely on city-scale indicators and formal infrastructure datasets that are difficult to apply within informal settlement contexts characterized by limited spatial data availability and rapidly

changing settlement conditions [12–14]. Consequently, climate vulnerabilities and adaptive capacity within informal settlements remain insufficiently operationalised and spatially assessed. To address this limitation, Ndlangamandla and Du Plessis [5] developed the Resilience Assessment Framework for Informal Settlements (RAFIS), a context-sensitive framework structured around the resilience attributes of diversity, redundancy, modularity, and connectivity.

2.3 Overview of the RAFIS

RAFIS (see Fig. 1) consists of four phases: (1) identification of climate hazards, (2) identification of climate impacts, (3) assessment of vulnerable settlement components, and (4) identification of resilience interventions.

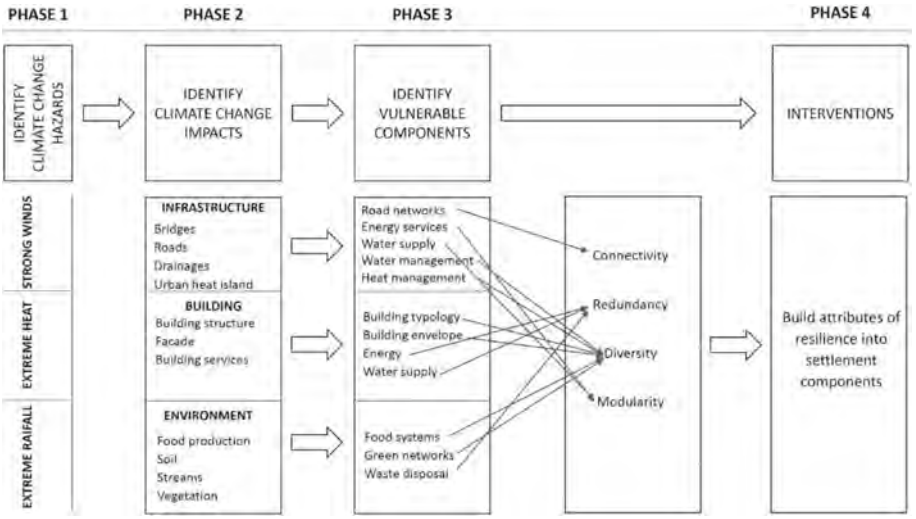


Fig. 1. Resilience assessment framework for informal settlements [5]

Phases 1 and 2 establish the climate hazard and impact context informing Phase 3, which forms the primary focus of this study. Phase 3 operationalises resilience attributes by translating these into measurable spatial indicators to assess buildings, infrastructure systems, and environmental resources at building and settlement scales. Phase 4 uses the assessment findings to inform climate-responsive upgrading interventions.

3 Research Methodology

This study adopted a mixed-method case study approach to apply RAFIS in the Msunduza informal settlement, Mbabane, Eswatini. Msunduza is characterized by high building density, inadequate infrastructure, poor drainage systems, and environmental exposure to flooding and heat stress. The settlement was selected due to its representative

characteristics of informal settlements within similar Global South contexts. The study operationalised the four phases of RAFIS through document analysis, expert interviews, and structured spatial mapping in this area.

3.1 Phase 1: Identification of Climate Hazards

The first phase involved identifying climate-related hazards to which the settlement should adapt. Document analysis was conducted using climate reports, policy documents, previous studies, and spatial information relating to Mbabane and informal settlements in Eswatini. The documents were purposely selected based on their relevance to climate change, urban vulnerability, and informal settlements. They were analysed thematically to identify recurring climate hazards affecting informal settlements.

3.2 Phase 2: Identification of Climate Impacts

The second phase focused on identifying impacts of the identified climate hazards on buildings, infrastructure systems, and environmental resources within the settlement. Semi-structured interviews were conducted with ten purposively selected experts from climate change, urban planning, environmental management, and disaster risk management institutions in Eswatini.

The interview data were coded and grouped into recurring climate impact and vulnerability themes through thematic analysis. The findings informed the assessment variables and indicators used in Phase 3.

3.3 Phase 3: Assessment of Vulnerable Components

The third phase formed the primary focus of the study and involved structured spatial mapping of buildings, infrastructure systems, and environmental resources within the settlement to identify areas that require interventions to improve their adaptive capacity to the risks identified. Systematic random sampling was used to select a sample of 230 buildings for assessment. Data collection was conducted using Epicollect5 to capture geolocated quantitative and qualitative spatial data. A georeferenced mapping checklist derived from RAFIS assessment variables was used to operationalise the resilience attributes and environmental resources.

Diversity indicators assessed the availability of a variety of systems and resources supporting adaptive capacity, redundancy indicators assessed the availability of backup systems during disruptions, connectivity indicators assessed the linkage and accessibility of infrastructure networks, while modularity indicators assessed the ability of subsystems to function independently during disruptions.

The assessment included building materials and thermal characteristics, drainage systems, water and energy access, road and pathway connectivity, vegetation and environmental resources, and waste disposal. The collected data were analysed using QGIS for geospatial analysis and SPSS for descriptive statistical analysis, including frequency distributions and percentage analysis of resilience indicators.

3.4 Phase 4: Identification of Resilience Interventions

The final phase involved proposing preliminary climate-responsive upgrading interventions based on the vulnerabilities identified during the assessment. The proposed interventions focused on drainage improvement, environmental protection, infrastructure connectivity, and increased service redundancy within the settlement.

4 Findings and Discussion

4.1 Climate Hazards and Impacts

The document analysis identified intense rainfall and extreme heat as major climate-related hazards affecting Msunduza. Expert interviews further identified flooding, infrastructure disruption, thermal discomfort, environmental degradation, and mobility challenges as major impacts affecting settlement systems. The identified hazards and impacts informed the selection of vulnerable settlement components (see Fig. 2) and assessment indicators used in Phase 3.

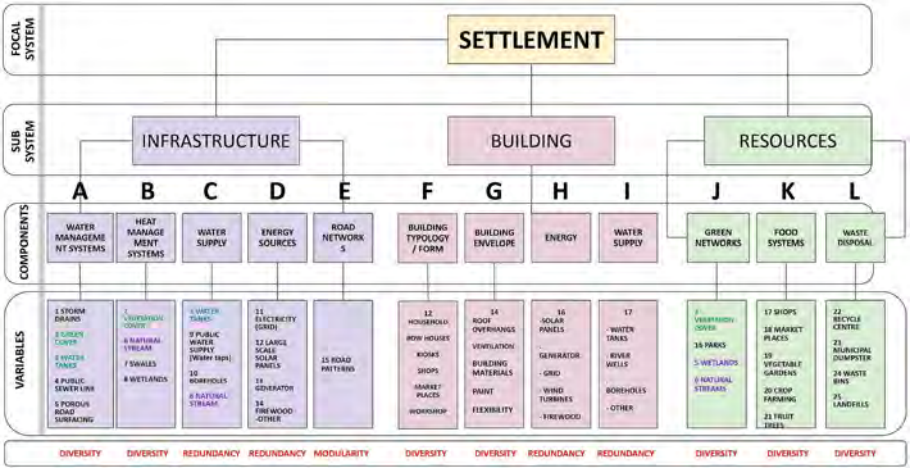


Fig. 2. Hierarchical structure of settlement subsystems, affected components, resilience attributes, and resilience indicators used in RAFIS. View high resolution figure here.

4.2 Assessment of Resilience Attributes and Adaptive Capacity

The assessment revealed varying levels of adaptive capacity across buildings, infrastructure systems, and environmental resources within the settlement. The findings demonstrated that the presence or absence of resilience attributes such as diversity, redundancy, connectivity, and modularity influenced the adaptive capacity of settlement subsystems.

Table 1 summarises the assessment of settlement subsystems based on the resilience attributes operationalised through RAFIS indicators. The assessment revealed low

Table 1. Assessment of adaptive capacity and proposed interventions

Vulnerable Component	Climate Impact	Indicator	Indicator Assessment	Adaptive Capacity Status	Proposed Intervention
Drainage systems	Flooding	Drainage network continuity	Disconnected drainage channels	Low	Improve drainage connectivity
Water systems	Water disruption	Backup water systems	Limited backup water systems	Low	Introduce alternative water storage systems
Buildings	Heat stress	Variety of passive cooling technologies	Limited variation in passive cooling strategies	Low	Increase passive cooling and material diversity
Road networks	Mobility disruption	Pathway and road accessibility	Fragmented pathways and circulation routes	Low	Improve pathway and road connectivity
Energy systems	Power disruption	Backup energy systems	Limited backup energy systems	Low	Introduce alternative energy systems
Vegetation systems	Heat exposure	Presence of vegetation & wetlands	Limited green infrastructure coverage	Moderate	Protect and expand green networks

Poor – No trace of any resilience attributes **Moderate** – at least one alternative exists as a backup or to provide diversity. **Good** – sufficient alternative systems or functional diversity exists.

adaptive capacity across several settlement subsystems, particularly drainage systems, buildings, water systems, and infrastructure networks.

Drainage systems demonstrated low adaptive capacity due to weak connectivity between drainage channels and inadequate stormwater management infrastructure. Fragmented infrastructure networks further reduced mobility and emergency accessibility during extreme rainfall events. Similarly, buildings demonstrated low adaptive capacity to heat stress due to limited diversity in passive cooling strategies and the widespread use of corrugated metal roofing materials.

Water and energy systems also demonstrated low redundancy due to limited backup systems available during service disruptions, reducing the ability of households to maintain access to essential services during climate-related disturbances. In contrast, environmental resources such as wetlands, vegetation, and food systems demonstrated comparatively higher adaptive capacity through stormwater regulation, shading, and localised cooling effects.

The spatial distribution of vulnerability patterns identified through RAFIS is illustrated in Fig. 3. The spatial analysis revealed concentrations of flood vulnerability along wetland and stream corridors, while densely built-up areas with limited vegetation cover demonstrated increased heat vulnerability.

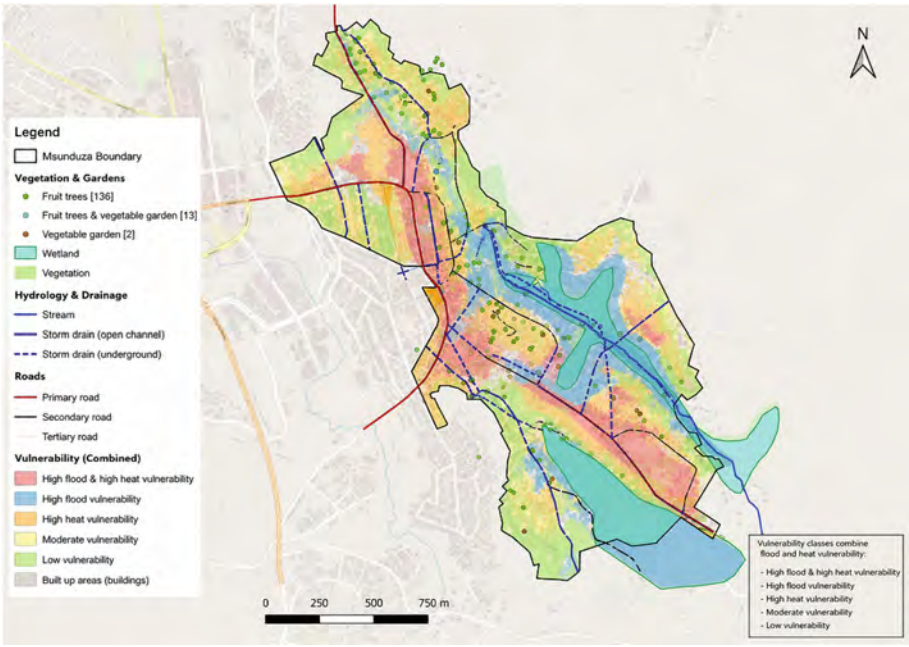


Fig. 3. Spatial distribution of climate vulnerability hotspots and environmental resources in Msunduza informal settlement [5]. View high resolution figure here.

Areas where high flood and high heat vulnerability intersect represent zones with the lowest adaptive capacity within the settlement. These areas are characterised by inadequate drainage systems, limited environmental buffering capacity, fragmented infrastructure connectivity, and dense built-up conditions. In contrast, wetlands, vegetation systems, and food-producing landscapes (e.g. fruit trees and vegetable gardens) enhance adaptive capacity through ecosystem-based buffering and localised cooling effects.

Table 1 and Fig. 3 illustrate how resilience attributes shape adaptive capacity across settlement subsystems, showing how indicators can reveal vulnerability patterns and inform climate-responsive upgrading. The findings suggest that upgrading strategies should prioritise improved drainage, strengthened infrastructure connectivity, protection of wetlands and green networks, and the development of redundant water and energy systems. They also suggest that climate-responsive upgrading within informal settlements should prioritize improved drainage systems, increased infrastructure connectivity, protection of wetlands and green networks, and the development of redundant water and energy systems.

5 Conclusion

This study demonstrates the empirical application of the Resilience Assessment Framework for Informal Settlements (RAFIS) as a transferable approach for diagnosing climate vulnerabilities in data-scarce environments. By translating the resilience attributes of diversity, redundancy, modularity, and connectivity into measurable spatial indicators, the research was able to identify critical gaps in the adaptive capacity of building and infrastructure subsystems in the Msunduza informal settlement. The primary contribution of this work lies in providing a context-sensitive methodology that moves beyond city-scale assessments to support evidence-based, climate-responsive upgrading interventions. Ultimately, RAFIS offers a practical tool for practitioners to target specific spatial vulnerabilities, ensuring that resilience-building efforts in the Global South are grounded in the unique realities of informal settlement contexts.

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The Waterfront Paradox: Morphological Path Dependency and Increased Flood Risk in Ioannina, Greece

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Abstract. The urban development of Ioannina has historically been shaped by its proximity to Lake Pamvotis, where expansion from the elevated castle toward the lakeshore transformed a defensive boundary into a dense urban front. Under contemporary climate change, this spatial advantage has become a structural vulnerability. This study integrates official flood scenarios (50-, 100-, and 1000-year return periods) with spatial and morphological analysis to assess infrastructure exposure along the urban lakeside zone of Ioannina, from the Limnopoula area to the Katsika district. Results show that post-1950 densification on low-lying and reclaimed land significantly increases exposure of residential areas, tourism facilities, and transport networks. The findings demonstrate that current flood vulnerability is embedded in historical urban growth patterns and highlight the need to integrate morphological indicators into climate-adaptive planning for historic lakeside cities.

Keywords: Flood Risk Assessment · Climate Change Adaptation · Waterfront Urban Development · Urban Morphology · Infrastructure Resilience · Ioannina · Greece

1 Introduction

Urban settlements have historically developed along lake and river systems to facilitate trade and defense. In recent decades, accelerated urbanization and climate change have situated these historic urban cores within environmentally sensitive and high-risk zones [1–3]. The expansion of human activities along waterfronts, from European coasts to inland lakeshores, has intensified these risks by increasing transport infrastructure and reducing green spaces, which in turn raises impervious surface area and runoff [4– 6].This historical infrastructure lock-in leads to morphological path dependency, in which initial spatial decisions constrain the potential for contemporary adaptation [7, 8]. Traditional gray infrastructure measures are increasingly inadequate, particularly in Mediterranean catchments [9], whereas environmentally sustainable alternatives such as

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Blue-Green Infrastructure present opportunities to enhance resilience [10, 11]. Despite this, research directly linking specific hydrological risks to the long-term evolution of urban morphology remains limited [12, 13]. This study uses Ioannina as a case to investigate how historical land reclamation and densification, typical of low-lying waterfront communities, embed structural vulnerabilities and shape the mechanisms underlying morphological flood path dependency.

2 Urban and Historical Context

Ioannina is situated within a closed basin in northwestern Greece, extending along the western shoreline of Lake Pamvotis. The basin's morphology significantly influences hydrological behavior, as limited natural drainage heightens the sensitivity of lake margins to intense precipitation events. Elevation increases gradually from the lakeshore toward the urban core, creating a distinct gradient between low-lying waterfront areas and higher inland districts.

The earliest settlement was established at the most defensible elevated location along the lakeshore, within the castle of Ioannina. Historically, the lake functioned both as a defensive boundary and as a resource base, while the adjacent low-lying areas were primarily utilized for agriculture and vegetable cultivation.

A major transformation occurred after 1950, when land reclamation and shoreline stabilization enabled urban expansion toward the lake. Former agricultural land was progressively replaced by multi-story residential buildings, hotel complexes, road infrastructure, and recreational facilities. Post-war densification led to a substantial reduction in permeable surfaces and an increase in building coverage within the newly reclaimed, low-lying lakefront areas. Figure 1 illustrates the study area, delineated by a red dotted line, which extends approximately 500 m from Lake Pamvotis toward the city center of Ioannina and represents the zone of historical urban expansion.

Consequently, the lakeside zone transitioned from a low-density, absorptive landscape to a high-value urban frontage that concentrates residential, tourism, and transport infrastructure within hydrologically sensitive terrain. This historical transition from elevated defensive settlement to dense lakeside development constitutes the structural basis for contemporary flood exposure.

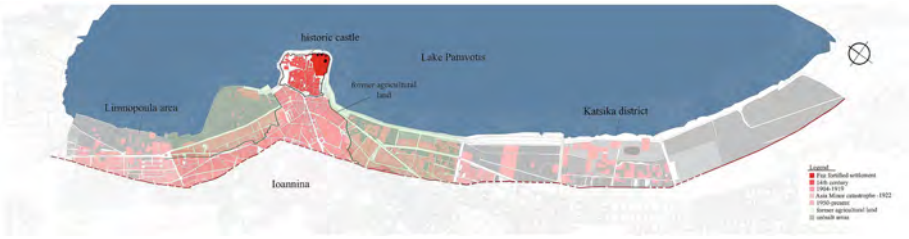


Fig. 1. Historical urban expansion of Ioannina from the castle toward Lake Pamvotis

3 Identified Research Gap

Flood-risk assessments frequently prioritize hydrological modeling, often neglecting the influence of long-term urban morphology on exposure. In historic lakeside cities, vulnerability is determined not only by topography and rainfall but also by patterns of urban expansion, land reclamation, densification, and infrastructure concentration. Few studies integrate predictive flood modeling with analyses of historical urban growth and land-use change, resulting in limited understanding of how heritage-driven urban form affects flood risk. This research gap is particularly significant in Ioannina, where urban development has transitioned from elevated, fortified cores to low-lying lakeside areas. Addressing this issue is crucial for adaptive planning that reconciles cultural heritage preservation, economic development, and climate resilience.

4 Methodology

This study integrates flood-hazard modeling with spatial analysis of urban form and historical expansion, employing a three-stage research design. First, historical maps and planning documents were collected and digitized to trace the spatial evolution of Ioannina from its elevated historic core toward the lakeside zone, identifying key phases of development, particularly post-1950 expansion into formerly agricultural and low-lying areas. Second, official flood-hazard maps produced by the Greek Ministry of Environment and Energy were analyzed to assess projected inundation under 50-, 100-, and 1000-year return periods, including the spatial coverage and depth of flooding along the urban frontage of Lake Pamvotis. Third, projected flood zones were examined in relation to existing land uses and infrastructure distribution in order to quantify the proportion of built-up areas affected, the extent of impacted road networks, the exposure of tourism facilities, and the relationship between flood depth and urban density (Fig. 2). This integrated approach provides the interpretation of contemporary flood exposure in relation to long-term morphological development and inherited spatial configurations.



Fig. 2. Current land-use distribution along the Ioannina lakeshore highlights residential, tourism, and transport infrastructure.

5 Results

Flood simulations indicate a progressive inland expansion of inundation from the lakeshore toward the urban core as return periods increase. In the 50-year scenario, flooding is primarily concentrated in low-lying residential, recreational, and tourism zones adjacent to Lake Pamvotis (Fig. 3). The 100-year scenario shows inundation extending further into consolidated urban districts, including areas near the historic core of Ioannina (Fig. 4). The 1000-year scenario results in widespread flooding across densely populated residential and commercial sectors (Fig. 5). In all scenarios, projected flood depths in exposed areas reach approximately 2 m, and both the extent and continuity of inundation increase nonlinearly with longer return periods.

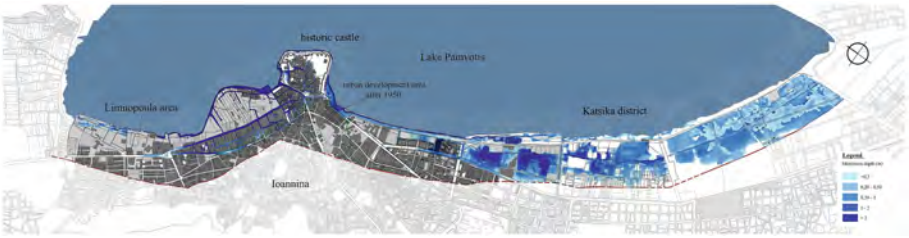


Fig. 3. Projected flood depth along the Ioannina lakeshore for 50-year return period

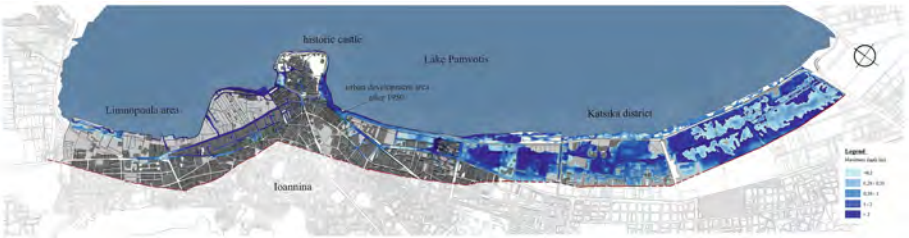


Fig. 4. Projected flood depth along the Ioannina lakeshore for 100-year return period

Spatial overlay analysis reveals a substantial overlap between projected flood zones and areas developed after 1950. A significant proportion of multi-story residential buildings and tourism facilities are situated within the 100-year flood zone, while major road corridors parallel to the lakeshore intersect projected inundation areas in all scenarios. As return periods increase, the proportion of built-up surfaces and transport infrastructure affected rises disproportionately with the expansion of flood extent, indicating a concentration of assets in low-elevation terrain (Fig. 6).

These patterns demonstrate a direct correlation between urban density and flood exposure. Areas developed during the post-war period, characterized by high building coverage and limited permeable surfaces, exhibit the greatest vulnerability. The historic castle represents a distinct case; although located at a higher elevation, its enclosed

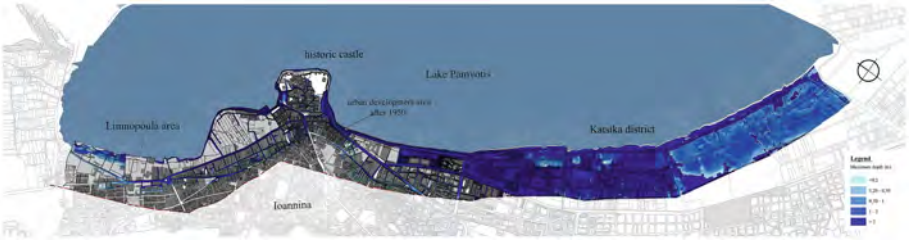


Fig. 5. Projected flood depth along the Ioannina lakeshore for 1000-year return period



Fig. 6. Projected flood depth for the 100-year return period and affected land uses along the Ioannina lakeshore.

structure restricts drainage capacity, resulting in localized water accumulation during extreme events. Overall, the findings confirm that contemporary flood risk is structurally embedded in the city's morphological evolution, particularly through the transformation of former agricultural land along the lakeshore into dense urban frontage.

6 Discussion

Flood risk along the lakeside of Ioannina arises not only from climate change but is also rooted in the city's historical urban form. The transformation of the former waterfront boundary into a dense urban front has concentrated housing, tourism, and infrastructure in low-lying areas, thereby increasing exposure. This amenity-driven vulnerability is similarly observed in other Mediterranean and European historic waterfronts that have been altered by post-industrial redevelopment. The prioritization of higher ground and the clustering of critical infrastructure along Lake Pamvotis further constrain adaptive capacity. In this high-density context, embankments and retaining walls remain inadequate.

The lakeside expansion exhibits a linear, orthogonal layout defined by the shoreline. Major roads run parallel to the lake, concentrating infrastructure within vulnerable zones. Rectangular blocks extend inland in a repetitive grid, maximizing frontage but increasing impervious surfaces and channeling runoff toward limited drainage points. In contrast, the historic castle district maintains a compact, irregular form within defensive walls, where narrow passages and few outlets result in localized water accumulation during intense rainfall. Collectively, these urban morphologies impose distinct hydrological constraints on the city.

This study is part of a broader doctoral project examining flood risk in Greek lakeside cities, including Kastoria, as well as selected European and Balkan cases. Kastoria provides a useful comparison because its lake is not a closed basin, and the city develops along a narrow waterfront strip bordered by steep terrain. While this zone accommodates housing, public buildings, and tourism, its limited width restricts the availability of expansive public areas or flood-buffer zones. This configuration produces a distinct spatial relationship between urban development and hydrological processes, which will be further analyzed as the research progresses.

6.1 Scenarios

Two conceptual scenarios illustrate the potential impact of alternative lakeside development strategies on flood resilience and urban sustainability. The first scenario considers the lakeshore remaining undeveloped for residential purposes since 1950, serving instead as agricultural land and public green space. In this scenario, the area would retain a high proportion of public space, thereby reducing the number of buildings exposed to flooding and providing a natural buffer that absorbs and slows runoff from adjacent urban areas.

The second scenario represents the current urban pattern, characterized by existing development but incorporating partial buffer zones to restrict future construction. Although this approach is more feasible given the established urban structures, it offers only limited flood protection compared to the first scenario.

In comparison, preserving ecological space maximizes flood resilience, while controlled development with designated buffer zones constitutes a pragmatic, though less protective, adaptation strategy. The findings are consistent with path-dependency theory in urban morphology, illustrating that early spatial decisions shape long-term environmental risk. When high-value infrastructure is concentrated along waterfront edges, adaptive capacity is significantly limited.

6.2 Uncertainty Acknowledgement

Flood projections utilize the Greek Ministry of Environment and Energy's modeling program, which incorporates historical rainfall data and simulates 50-, 100-, and 1000-year return periods. These scenarios represent modeled conditions and do not account for all future variability, such as changes in precipitation patterns, extreme events, or ongoing urban development along the lakeshore. Consequently, actual flood extents and depths may vary, underscoring the necessity for flexible and adaptive planning strategies.

7 Conclusions

Flood vulnerability along the shore of Lake Pamvotis in Ioannina was assessed by integrating multi-scenario flood modeling with spatial urban analysis. Findings demonstrate that densification since 1950 has substantially increased exposure, with critical infrastructure now situated within projected flood zones. Historical patterns of urban expansion have directly influenced current vulnerability. The "cost of the view" is both economic and structural, as the lakeshore's appeal has limited adaptive capacity. To

promote climate-responsive urban design, recommended measures include restricting further population growth within 100-year flood zones, expanding permeable surfaces along the lakefront corridor, and incorporating flood hazard maps into building permit procedures. Additional strategies involve redesigning the lakefront as flood-adaptive infrastructure and implementing adaptive solutions for critical road segments. Although the analysis centers on Ioannina, the methodological framework is broadly applicable to other historic lakeside cities where environmental risk coincides with urban desirability.

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Operationalizing Systems Thinking for Climate Risk Assessment in the Built Environment: Insights from a Participatory Workshop

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Abstract. Climate change generates cascading risks that propagate through interconnected physical, social, and environmental systems, creating complex challenges for the built environment. Effective climate risk assessment and adaptation planning therefore require systems-based lens and methods capable of revealing interdependencies, emergent behavior, and system-wide vulnerabilities. However, prevailing approaches in built environment practice often treat risks as isolated events, relying on risk checklists and matrices that overlook feedback loops, spatial–temporal interactions, and cross-system dependencies. Although the value of systems thinking for climate adaptation is widely recognized, research on systems-based climate risk assessment is rather limited. This paper presents initial findings from an ongoing research project that investigates how systems thinking can be operationalized for climate adaptation planning in the built environment by conducting participatory workshops with domain experts. Using university campuses as an initial testbed, nine experts evaluated alternative methods for assessment of overheating risk in buildings. They produced visualizations – including a process model, risk map, a conceptual AI-enabled automated mapping tool and a rich picture to demonstrate how systems thinking can be used by the estate management teams. Findings from this workshop show that systems thinking provides a useful framework for understanding system behavior perceived differently by diverse stakeholders and communicating risk information for climate resilient systems. The study contributes to academic debate on embedding systems thinking into climate adaptation planning, particularly why and how it can be mobilized, and offers practical insights for advancing systems-based climate risk assessment in the built environment.

Keywords: climate risk · climate adaptation planning · resilience · systems thinking · built environment

1 Introduction

Climate change constitutes a global systemic risk characterized by interdependence, non-linearity, cascading effects, and deep uncertainty (Haas et al., 2022). Unlike discrete hazards, systemic risks propagate across interconnected physical, social, economic

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and institutional systems, producing compounding and often counterintuitive outcomes. In such complex contexts, cause–effect relationships are neither linear nor stable, and interventions may generate unintended consequences over time, leading to futures that are difficult to predict (Haas et al., 2022). The built environment is particularly exposed to systemic climate risks. Climate-induced changes such as overheating, flooding or energy stress do not operate in isolation, but rather they interact with design decisions, operational practices, user behaviors, as well as institutional priorities (Adger et al., 2022). However, prevailing Climate Risk Assessment (CRA) practices in the built environment remain largely dominated by linear and reductionist methods such as risk registers or high-level probability matrices (Hochrainer-Stigler et al., 2024). While these methods offer structured and auditable outputs, they stop short of representing cross-system dependencies, feedback loops, temporal dynamics and the evolving nature of vulnerabilities. In response, systems thinking is increasingly advocated as a conceptual foundation for transformative climate adaptation. Unlike linear approaches, systems thinking offers a more suitable lens for understanding systemic risks as it prioritizes and emphasizes interrelationships, boundary considerations, feedback mechanisms, and emergent behaviour (Bi et al., 2021). Yet, despite a broad consensus on its value, the practical operationalization of systems thinking remains underexplored. To address an operationalization gap between theoretical debates and how systems thinking can be integrated within everyday practices of planning and decision making in the built environment, we conducted an exploratory participatory workshop with domain experts. Participants first engaged in a linear risk-framing exercise and subsequently developed systems-based visualizations to reframe the systemic climate risk context. By analysing the artefacts and discussion notes, this study contributes empirical insights into how systems thinking can move from rhetorical affirmation to practice.

2 Systems Thinking: Conceptual Foundations

Systems thinking refers to a broad family of theoretical perspectives and methodological approaches concerned with understanding and intervening in complex problem situations characterised by interdependence, feedback, and emergent behaviour. Systems thinking is commonly defined as the capacity to identify interrelationships, consider multiple perspectives, and reason across system boundaries (Arnold and Wade, 2015). Thus, the focus is on patterns of interaction and structural drivers of behaviour rather than on isolated components or linear causality (Senge, 1990). Foundational work in systems dynamics (Forrester, 1971; Sterman, 2000) demonstrates how feedback-rich systems lead to counterintuitive behaviour and persistent decision failures despite increased information when misinterpreted through linear models. It evolved from optimisation-oriented approaches toward learning-oriented and pluralist approaches as it became evident that many real-world problems involve contested values, shifting objectives, and socially constructed boundaries (Checkland, 1985). Systems thinking therefore, functions both as a reflective and normative practice that can surface excluded perspectives in complex, participatory contexts (Midgley and Pinzon, 2011). These characteristics position systems thinking as a suitable conceptual lens for systemic risk contexts, where complexity, uncertainty and emergence challenge traditional planning.

3 Climate Risk Assessment: Traditional vs Systems Approaches

Traditional CRA in the built environment commonly relies on factor-based identification, risk checklists and probability-impact matrices. Although these methods structure information to support accountability and compliance, they implicitly assume that risks are discrete, bounded, and largely independent. Such assumptions are increasingly at odds with climate change as a global systemic risk. There have been increasing calls for a fundamental shift in climate risk management grounded in systems thinking and modelling (Deubelli and Mechler, 2021). However, evidence suggests an operationalization gap—systemic models and computational simulations developed in research contexts remain underutilized in practice due to institutional inertia, limited capacity, and unfamiliarity among practitioners (Yap et al., 2025; Hochrainer-Stigler et al., 2024). Efforts to operationalise systemic risk assessment increasingly emphasize knowledge co-production and participatory processes as ways to integrate local knowledge, diverse expertise, and different perspectives, thus "humanising" complexity by integrating design thinking with systems thinking (Liedtka and Locatelli, 2023). Despite these developments, there remains limited empirical evidence on how systems thinking principles can be embedded in climate risk assessment workflows in the built environment. This study addresses this gap by experimentally comparing linear and systems-based framing within a structured participatory setting.

4 Research Methodology

4.1 Research Design

This study adopted an exploratory, qualitative research design to investigate how systems thinking can be operationalised within CRA practice in the built environment. Given that systems thinking is inherently concerned with sense-making, inter-relationships, and multiple perspectives, a participatory workshop approach was selected to enable collaborative inquiry and co-production of knowledge. The methodological approach was informed by principles of action-oriented and systems-based inquiry, emphasising iterative learning, visualisation, and stakeholder engagement.

4.2 Case Context and Participant Selection

A university campus was selected as an initial testbed for operationalising systems thinking for climate adaptation planning. Campuses function as complex socio-technical systems comprising interconnected physical infrastructure (buildings, utilities), social systems (students, staff, governance structures), and environmental interfaces (landscape, water systems, energy networks). While offering a manageable contextual boundary, it has sufficient complexity to explore cross-system inter-dependencies and multiple stakeholder decision-making, and is therefore representa-tive of broader built environment systems.

Nine domain experts who are members of the Climate Resilient Built Environment Research Cluster (CRESBE) in the University of Reading participated in the study.

Participants were selected to reflect diverse expertise relevant to climate resilience and systems thinking, but also for their ability to critically engage with CRA processes. Five of the experts had more than 20 years of academic and professional experience. Academic background/research interests of the participants were diverse including construction management and sociology, digital technologies and energy policy, risk management and renewable energy systems. This diversity enabled multiple perspectives on risk drivers, system behaviour, and adaptation priorities. The relatively small group size enabled in-depth discussion and iterative refinement of visual artefacts while maintaining diversity of viewpoints.

4.3 Workshop Design

The two-hour workshop was structured as an interactive, practice-oriented session. It was designed as a structured participatory workshop to compare linear and systems-based approaches to CRA and to co-develop systems-informed tools using visualizations. The workshop had three components: a linear risk framing exercise, systems-based reframing using visualizations, and discussion of visualizations to make sense of how systems thinking can be incorporated into CRA. It began with a facilitated discussion on the meaning of risk and the limitations of prevailing risk assessment practices. Rather than relying solely on formal definitions, the discussion was grounded in everyday examples to surface participants' tacit assumptions about risk, responsibility, control and boundaries. This initial dialogue was then explicitly linked to the built environment, enabling participants to reflect on how conventional risk registers and linear assessment tools perform in complex, climate-driven contexts. The workshop was motivated by a shared concern-limited operationalisation of systems thinking in routine planning and decision-making. For systems-based reframing participants were then invited in groups to reconsider climate adaptation planning approaches using systems thinking principles. Here, participants were invited to collaboratively develop systems-oriented visualisations considering the "overheating risk in campus buildings". These artefacts produced by four groups functioned both as analytical tools and as boundary objects supporting dialogue across disciplinary perspectives. Finally, participants discussed how systems approaches as described by the co-developed artefacts support shared understanding, and the design of adaptation interventions.

5 Workshop Findings

The workshop findings are organised around four conceptual visuals. While all groups worked from a shared prompt, developing a visual that can be used by the Estates Department to operationalise systems thinking for climate resilience, the artefacts they produced differed markedly in emphasis, structure and implicit theory of action (Fig. 1). Each visual favoured certain dimensions of the system while backgrounding others. Thus, these visuals do not function as technical diagrams but as boundary objects that support dialogue, reflection, and learning across disciplinary boundaries. Together, they demonstrate that all the participants modelled the systemic risk as an ongoing, relational and multi-perspective process, illustrating how practitioners conceptualize risks differently when invited to move beyond linear CRA templates.

5.1 V1. An Iterative, Learning-Oriented Process Model

The first group responded to the task by modelling not the risk system itself, but the process by which people should talk about and engage with systemic climate risk (Fig. 1a). Their artefact represents a high-level, iterative process for CRA. Rather than tracing linear consequences of a hazard, the model starts with diverse inputs: stakeholder voices, lived experiences, assumptions, and constraints. These inputs are brought into a facilitated cycle of reframing through mapping, dialogue, and evaluation. It highlights the relationships between social, technical, and organisational variables, accommodates multiple system boundaries, and uncertainty. The group discerned between two layers: (i) an auditable layer, satisfying institutional requirements (e.g. risk registers), and (ii) a learning-oriented systems layer that surfaces assumptions, boundary choices and interdependencies; feeding into the former. This visual demonstrates that, when prompted to think systemically, participants prioritised governance over technical modelling.

5.2 V2. Visualising Information in a Shared Digital Environment

The second group focused less on a procedural flow and more on how information about systemic risk could be captured, made visible, shareable and quantifiable (Fig. 1b). Their artefact depicts a collaborative digital workspace in which system vulnerabilities and climate risk are captured by AI. Unlike the first group's process model, this visual highlights information architecture with pre-configured elements (AI-informed causal loops) that provide starting points, but which users can customise. The emphasis is on visualising relationships so that trade-offs and leverage points become discussable. Here, systemic risk is modelled as distributed knowledge rather than as a fixed chain of impacts. Simulations allow users to test interventions and assess consequences across scenarios. The digital environment functions as an enabler of collective systems thinking, not an automated decision-maker.

5.3 V3. A Map of Climate Risk Drivers and Impacts

The third group (Fig. 1c) produced a dynamic conceptual map linking causes, exposures, vulnerabilities, and impacts within a system. Compared to the previous two artefacts, this visual more closely resembles a technical systems diagram. However, it departs from linear CRA formats by explicitly allowing relationships to be strengthened, weakened, or redirected over time. This group's discussion revealed that when participants sought to "describe the system," they gravitated toward technical features as anchors for mapping relationships. Systemic understanding was articulated through the language of physical and functional components. Causes can arise from external stressors, human activity, and asset capacity; impacts span functional, and systemic domains; stakeholders both influence and are affected by system dynamics. Recommended tasks (e.g. dependency mapping) are embedded within the map, reinforcing its action-oriented nature. This artefact shows that systemic modelling shifts attention towards adaptive decision-making rather than classification of factors.

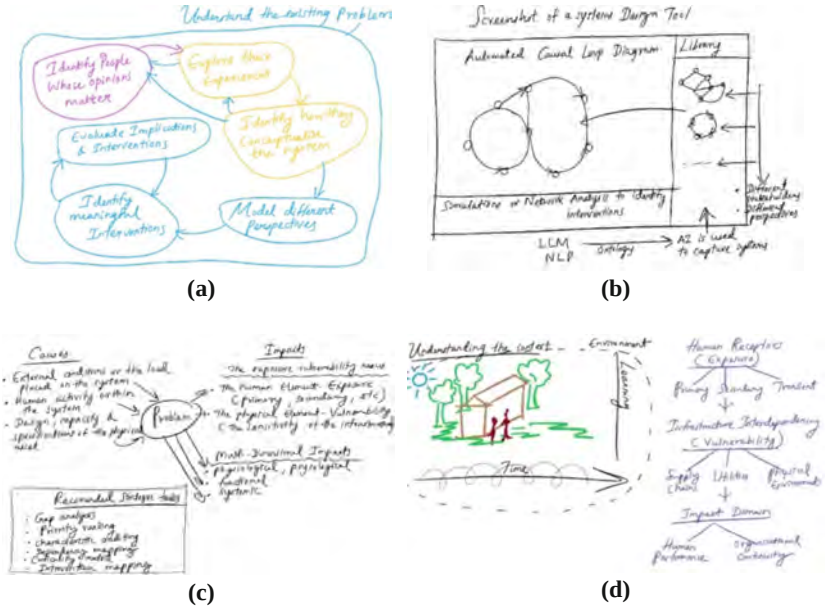


Fig. 1 **a**. Process model for CRA (V1). **b**. A tool for visualizing information (V2). **c** A map of risk drivers and impacts (V3). **d**. A rich picture (V4)

5.4 V4. Contextualising Risk Through Situational Mapping

The fourth group (Fig. 1d) attempted to visualise the broader context within which the climate risk unfolds. Their visual includes: a rich picture situating campus buildings within urban and ecological environments; a temporal graph of learning and adaptation; and a hierarchy linking receptors, impacts, and interventions. It frames climate risk as a situated condition shaped by spatial relationships, actor networks, and temporal change. The emphasis is not on discrete variables but on the context in which decisions occur. The group underscored that planning requires movement between perspectives—zooming in on vulnerabilities while zooming out to systems context.

6 Discussion of Findings

Overall, although each group emphasised a different dimension—process (V1), information (V2), mapping of risk drivers and impacts (V3), and context (V4)—all departed from linear risk logic to create representations that are iterative, interconnected and adaptive. The visuals demonstrate that systemic climate risk cannot be captured through a single diagram or analytical lens. Together, the visuals suggest that effective CRA requires navigating among multiple representations, using them as complementary boundary objects to sustain dialogue and learning. The results, therefore, indicate that operationalising systems thinking in CRA is about shifting from linear risk depiction to an ongoing, multi-perspective process of systemic inquiry that requires alternative governance and information models, which aligns with recommendations of Bi et al. (2021) about environmental risk assessment,

7 Recommendations for Climate Adaptation Planning

Based on the findings from this workshop, following are proposed for climate adaptation planning in university campuses:

1. Risk checklists fall short of understanding systemic impacts of climate change. Establish climate adaptation as a continuous, iterative learning process that complements formal risk registers with systems-based inquiry into uncertainty, and interdependencies.
2. Build systems-thinking capability within Estates and Facilities teams through training, interdisciplinary collaboration, and the development of adaptive decision-making skills.
3. Create cross-departmental teams comprised of multiple disciplines and stakeholders - administrative units such as Estates, academics, students, and external stakeholders into shared resilience decision-making.
4. Embed participatory systems-mapping workshops into estate planning and strategic planning processes to capture operational knowledge, lived experience, and diverse stakeholder perspectives on systemic impacts.
5. Shift from isolated asset-level assessments to dynamic systems mapping that identifies dependencies, cascading failures, and critical vulnerabilities across campus operations and infrastructure.
6. Visualisation supports systems understanding and collaborative planning. Develop a shared digital climate risk platform to visualise campus interdependencies, integrate climate and asset data, and support collaborative scenario testing.
7. Integrate climate adaptation with net-zero, biodiversity, health, and campus transformation strategies to avoid maladaptation and maximise co-benefits.
8. Establish monitoring, feedback, and organisational learning mechanisms that regularly review adaptation effectiveness, update assumptions, and incorporate lessons learned from climate events.

8 Conclusions

In this study, we presented experimental findings from a comparison of linear and systems-based CRA approaches, examining how systems framing (re)shapes climate risk understanding. Workshop findings demonstrate that systems approaches are about designing processes and gathering and structuring information, knowledge, and evidence about system behaviour as perceived by the stakeholders. Co-developed, practice-oriented artefacts demonstrate an empirically grounded pathway for operationalising systems thinking in CRA. The participatory workshop also highlights the value of visual metaphors and rich pictures in eliciting discussion and facilitating dialogue across disciplinary boundaries. Recommendations are made for those responsible for climate adaptation planning in campuses. On the other hand, as an exploratory study with a small sample and a single test context, findings are not generalizable. The aim was not to produce definitive CRA models, but to generate practice-informed insights into how systems thinking principles can be embedded within real-world assessment processes. The workshop design developed in this study can be adapted for use in similar participatory research and professional settings to foster reflective dialogue and support

the co-production of systems-based approaches. Recommendations developed as a part of this study may provide practical insights for climate adaptation planning in other organisations.

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Building Urban Resilience in a Changing Climate: Green and Blue Infrastructure and Nature Based Solutions for Urban Redevelopment in Athens

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Abstract. Cities experience the impacts of high building density on microclimate, pedestrian comfort and UHI intensity exacerbated by climate change implications, increasing frequency of extreme events, obstructed mobility and downgraded infrastructure. In 2019 the Municipality of Athens initiated an urban redevelopment project under Athens Resilient City Strategy and EIB Natural Capital Finance Facility support, focusing on the integration of green and blue infrastructure and nature-based solutions in streets and squares aiming to upgrade environmental quality, promote biodiversity and build resilience to climate change impacts, setting quantitative targets and evaluation criteria. Proposed interventions at four locations vary due to diversity of the study areas, nevertheless, share a common approach which includes green corridors, infrastructure networks, rainwater drainage systems, pervious pavements and sustainable mobility measures. The project assessment included analytic simulations for calculation of microclimate improvement, pedestrian comfort improvement and building energy savings in two urban areas in summer conditions in current and future climate scenarios. At Exarchia area, a green corridor along Tositsa and Zosimadon streets, resulted in 2% ambient temperature reduction on a typical summer day and up to 13% energy savings at adjacent buildings in summer period of current climate and 10% in future scenario. A green corridor at the area of Lambrini resulted in 3% ambient temperature reduction and up to 20% lower cooling energy demands of adjacent buildings in current climate and up to 16% in future climate. Proposals include plans for monitoring microclimate development after project implementation with the installation of monitoring stations within and around the intervention areas.

Keywords: Urban redevelopment · Nature-based solutions · Green and blue infrastructure · Green corridors · Microclimate simulation · Building energy savings

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1 Introduction

Cities experience impacts of built density on microclimate, pedestrian comfort and UHI intensity exacerbated by climate change implications, increasing frequency of extreme events, obstructed mobility and downgraded infrastructure. The Municipality of Athens initiated in 2019 an urban redevelopment project under Athens Resilient City Strategy and EIB Natural Capital Finance Facility support, focusing on the integration of green and blue infrastructure and nature-based solutions in streets and squares aiming to upgrade environmental quality, promote biodiversity and build resilience to climate change impacts, setting quantitative targets and evaluation criteria. Proposed interventions at diverse locations vary, nevertheless, share a common approach with green corridors, rainwater drainage systems, pervious pavements and sustainable mobility measures [1, 2]. The project assessment included analytic simulations for microclimate and pedestrian comfort improvement and building energy savings at two sites, in summer conditions in current and future climate scenarios.

Climate change scenarios feature warmer summers, more frequent and intense heat waves, lower annual rainfall and longer droughts, extreme precipitation events of short duration and surface flooding [3]. Potential effects of such changes in cities include deteriorated pedestrian comfort, high energy requirements for cooling buildings, increased needs for watering urban plants, increased water runoff, potential failure of drainage networks and flooding. The assessment indicates that the proposals can effectively influence microclimate to support urban resilience. Summerime simulations reveal lower ambient and surface temperatures, moderate increase of humidity, thermal comfort improvement, cooling energy savings and fewer CO_2 emissions. Further benefits such as water runoff reduction and soil humidity increase were not evaluated but may also contribute to reducing urban vulnerability to climate change.

2 Case Study Sites

Urban redevelopment measures were proposed for four selected locations in Athens and two of them were assessed through analytic simulations, Exarcheia and Lambrini (Fig. 1). The diversity of the urban sites triggered different proposals, all sharing a common approach originated by resilient city strategies and nature-based solutions.

At the area of Exarcheia, in central Athens, the redevelopment focused on a green corridor between Strefi hill and the Archaeological Museum garden through two continuous streets, Tositsa st, a ~20 m wide street oriented ESE-WNW and Zosimadon st a ~8 m wide street with steep inclination oriented NE-SW, which are both surrounded by buildings of diverse heights from single-story to above 20 m high multi-story buildings. The proposed interventions expected to influence the microclimate conditions at pedestrian level are the addition of new trees and rain gardens on the side pavements, the replacement of pavements by high albedo sandstone slabs and granite cobble stones, the replacement of conventional asphalt by high albedo pavement on road surface, the improvement of the drainage network and enhancement of soil humidity, the minimization of road surfaces and promotion of sustainable mobility methods.



Fig. 1. a. Case study sites in Athens, b. Exarcheia area, c. Lambrini area.

At the area of Lambrini, in northern Athens, the redevelopment proposal focused on a green corridor between Greek Fighting Workers square and Kleonon Park through two perpendicular streets, Pandosias st oriented NNE-SSW, part of which is a pedestrian way, and Aliartou st oriented WNW-ESE. Both streets are ~9 m wide and surrounded by diverse height buildings. The proposed interventions expected to influence the microclimate conditions at pedestrian level are the addition of new trees on side pavements, on the pedestrian way and in the square, the preservation of numerous existing dense trees in the square, the replacement of hard pavements with water pervious surfaces (pervious cobble stone pavements, stabilized crushed ceramics and stabilized soil), the application of sustainable drainage systems and enhancement of soil humidity, the enlargement of side pavements along the streets and promotion of pedestrian circulation, the installation of water fountains in the square.

Street morphology and variant aspect ratios, result in Sky View Factor variations within the streets which affect solar incidence, heat dissipation, ambient temperatures and comfort. The different street axis orientation results in variable daily and annual shading patterns while at the square only vegetation is influencing shade (Fig. 2). Outdoor environmental improvement is expected to result by a. ambient temperature reduction due to tree shade, evapotranspiration and water evaporation, b. surface temperatures reduction due to tree shade, increased surface albedo (Exarcheia), increased water permeability (Lambrini) and higher soil humidity, c. air quality improvement due to pollutants reduction by plants' transpiration and sustainable mobility enhancement, d. pedestrian comfort improvement due to shading and lower temperatures, e. reduction of building energy needs for cooling and CO_2 emissions.

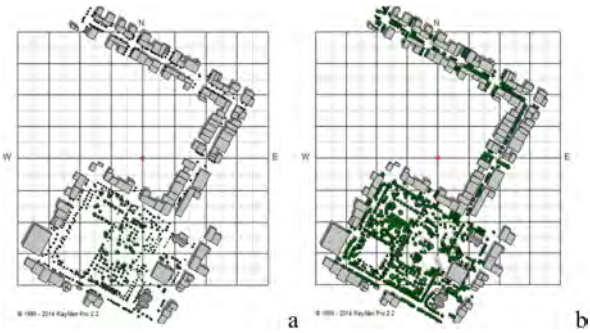


Fig. 2. Overshadowing study at Lambrini, on July 21st at noon a. base case b. proposed case.

3 Assessment Method

The assessment of proposed interventions is based on microclimate estimation in the study areas through analytic simulations before and after implementation and building energy performance estimation considering microclimate improvement results. To integrate microclimate differences in annual climate files, the mean air temperature of each month of the cooling period (from May to September) was modified in TEEKENAK's xml climate file, using mean daily air temperature reduction percentage calculated by envi-met for a typical summer day. In TEEKENAK vegetation effects were considered only through air temperature improvements.

3.1 Microclimate Simulations

Local microclimate analysis of the study areas through simulations with specialized software envi-met v.3 [4] concentrates on unfavorable hot summer conditions in current and future climate scenarios and reports on ambient temperatures, wind field, surface temperatures and thermal comfort indices. Each study area is simulated for a daily cycle in midsummer (21st July), in their original form and with proposed interventions, and the results are compared to examine the potential improvements. A winter simulation (21st January) is also performed to assess effects in the cold season.

The first microclimate evaluation is performed with a set of simulations considering current climate in Athens and a second evaluation follows with simulations considering future climate based on IPCC A1B scenario for 2050. Both data sets are obtained by the climate data processing software Meteonorm v7 [5] and imported as initial boundary conditions to the simulation tool (Table 1).

Buildings and street geometry, pavement material properties, vegetation type, height and foliage density are defined in the 3D area input files imported to the simulation tool i.e. an existing case model and a proposed case model for each location (Fig. 3). In the models, building heights range from 6 m to 24 m, vegetation includes existing trees 5 m–10 m high, grass and 32 new tree species, ground consists of hard and soft surfaces and grid resolution is 2 m for Exarcheia and 2.5 m for Lambrini. Pavement albedo varies between 0.2 and 0.4 in existing surfaces and up to 0.5 in proposals. Maximum LAD is 1.15 for most existing vegetation and up to 2 for proposals.

3.2 Building Energy Performance

To assess the influence of microclimate improvement over the built environment, a multistory apartment building is modeled and simulated according to the Greek National Energy Performance Method with TEE-KENAK v.1.31 [6], for calculating heating and cooling energy consumption, with monthly timestep (EN ISO 13790 [7]). An uninsulated residential building with single glazing timber windows and shutters is considered typical at the sites (Umasonry = 2.2 W/m^{2}K, Ubearing_structure = 3.4, Uroof = 3.05 W/m^{2}K Uwindows = 4.7 W/m^{2}K, Uwindows, with shutters = 4.0 W/m^{2}K), includes a local cooling system with air-conditioning split-units (EER = 3) in every apartment, a central heating system with oil-boiler and radiators (seasonal efficiency ns, h = 67%). Shading factors are used to account for nearby buildings shade. The building's annual energy consumption for heating and cooling is estimated under four cases of microclimate conditions as climate input: a. basecase microclimate in current climate, b. proposed case microclimate in current climate, c. basecase microclimate in future climate, d. proposed case microclimate in future climate. The single building energy savings due to microclimate improvement, are calculated by subtracting the annual energy consumption, under the proposed case microclimate, from the respective consumption under the base case microclimate. To estimate the influence of microclimate improvement on total building energy consumption within each site, energy savings per area unit are assumed to be the same for all buildings under consideration, i.e. a zone of built spaces along the redesigned streets extending 20 m beyond street boundaries and highly influenced by the proposed interventions. At Exarcheia this zone covers about 11600 m^2 i.e. 69600 m^2 of built space considering six floors per building and at Lambrini covers 33720 m^2 i.e. 74734 m^2 of built space considering both residential and public use buildings.

Table 1. Climate parameters imported in the simulation models of Exarcheia and Lambrini, as boundary conditions. July climate data were used for both current and future climate input.

Boundary conditions for simulations	Current climate	2050 IPCC A1B scenario
air temperature	27.6 °C	28 °C
relative humidity & specific humidity	57% & 7 g/kg	59% & 7 g/kg
wind velocity and direction at 10 m a.g.l.	1.6 m/s north	1.6 m/s north
upper soil layer temperature & humidity	21.1 °C & 40%	22.3 °C & 40%
solar radiation increase		10%



Fig. 3. Simulation input 3d models a. Exarcheia base case, b. Exarcheia proposed case, c. Lambrini base case, d. Lambrini proposed case. Points A, B, C correspond to reference locations.

4 Evaluation of Results in Contemporary and Future Climate

4.1 Microclimate Improvement

At Exarcheia the results of the microclimate study indicate the effects of proposed interventions on the two streets compared to the base case with focus in the summer period. Simulations with current climate data reveal air temperature reduction up to ~1 °C at summer midday within the study area, midday area averaged reduction 0.6 °C and daily area averaged reduction 0.6 °C representing 2% of the base case. Pavement surface temperature reduction up to 27 °C at midday is attributed to tree shade and high albedo surfaces with area averaged reduction ~11 °C. Improved thermal comfort for pedestrians with lower PET up to 27.5 °C at midday occurs below trees, area averaged PET reduction is 9.6 °C, and slightly increased PET at crossroads is due to light-colored pavements. Small wind velocity changes below 0.5 m/s have low impact on pedestrian comfort. Similarly, future climate simulations reveal max air temperature reduction 0.9 °C, midday area averaged reduction 0.6 °C and daily area averaged reduction 0.6 °C, i.e. 2% of the basecase, pavement surface temperature reduction at midday up to 28 °C and area averaged reduction ~11 °C, lower PET indices up to 29.5 °C below trees and area averaged PET reduction 9.8 °C at midday.

Extreme ambient temperatures and intense solar radiation at summer midday in Athens lead to inevitably high thermal stress for pedestrians at outdoor urban spaces. The simulation results of comfort indices (Fig. 4) indicate that the proposed interventions improve outdoor comfort and moderate pedestrian thermal stress towards conditions closer to the perception of neutrality according to comfort classifications [8].

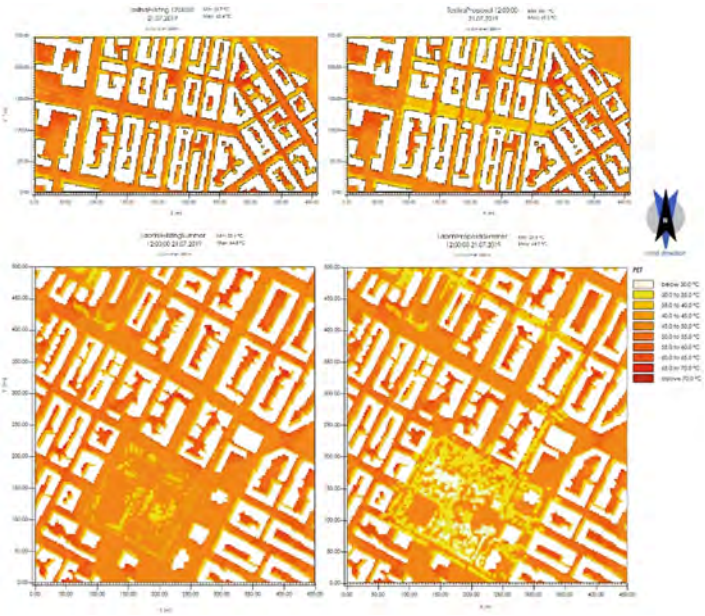


Fig. 4. PET thermal comfort indices at 1 m a.g.l at midsummer noon at Exarcheia (above) and Lambrini (below) in the base case (left) and the proposed case (right)

At Lambrini the microclimate study at the streets and the square presented larger improvement due to the interventions. Simulations with current climate reveal air temperature reduction up to 1.6 °C at summer midday, midday area averaged reduction 1.0 °C and daily area average reduction 0.9 °C representing 3% of the base case. Pavement surface temperature reduction above 26 °C at midday is due to tree shade, pervious surfaces and high albedo surfaces with area averaged reduction 9 °C. Improved pedestrian comfort with up to 25.8 °C lower PET indices at summer midday occurs below trees, area averaged PET reduction is 9.2 °C and spots of increased PET are due to relocated trees and exposed light-colored pavements. Small wind velocity changes have low impact on pedestrian comfort. Similarly, future climate simulations reveal max air temperature reduction 1.6 °C, midday area averaged reduction 0.9 °C, daily area averaged reduction 0.8 °C i.e. 2.7% of the basecase, pavement surface temperature reduction at midday above 27 °C with area averaged reduction nearly 10 °C, lower PET indices up to 27.9 °C at summer midday and area averaged PET reduction 8.8 °C.

4.2 Building Energy Savings and CO_2 Emissions

Microclimate simulations results for current and future climate are used to estimate potential building energy savings at the study areas by integrating air temperature changes in the climate input for building energy performance simulations. Because of negligible influence of the interventions in the winter period and the consumption for heating, only cooling energy savings are considered. At Exarcheia the results of building energy performance simulations with current climate input indicated that with a daily average

air temperature reduction by 2%, cooling energy demands in summer can be reduced up to 13% for the buildings adjacent to the project site. The results of simulations using future climate data indicated that with daily average air temperature reduction by 2% the cooling energy demands can be reduced up to 10%. At Lambrini the results of building energy performance simulations using current climate indicated that with the daily average air temperature reduction by 3%, cooling energy demands for the summer period can be reduced up to 20% for buildings adjacent to the project site. The results of simulations using future climate indicated that with average air temperature reduction by 2.7%, cooling energy demands can be reduced up to 16% (Fig. 5).

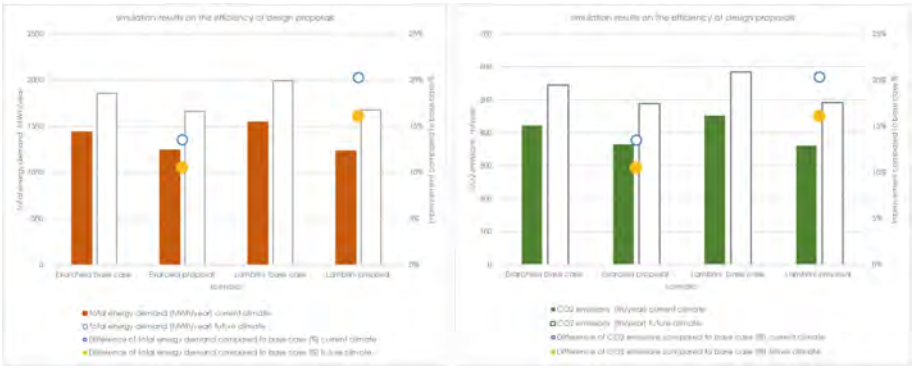


Fig. 5. Total energy demand and CO_2 emissions at Exarcheia and Lambrini estimated by building energy performance simulations for typical buildings using current and future climate input.

5 Conclusions

This study presented an evaluation of the potential effects of urban resilience strategies and nature-based solutions on microclimate improvement in current and future climate scenarios as well as the influence of such microclimate improvement in building energy consumption. The evaluation utilized analytic tools to simulate urban microclimate development and building energy performance for two case study sites in Athens. The proposed interventions under evaluation derive from a comprehensive urban redevelopment approach incorporating interventions such as green corridors, enhancement of vegetation and water elements, infrastructure networks, rainwater drainage systems, pervious pavements and sustainable mobility measures.

The microclimate improvement study focuses on the summer period and the effects of proposed interventions on ambient temperatures, comfort indices and building energy consumption for cooling. The simulation results for a typical warm summer day reveal lower ambient temperature up to 1.6 °C at midday as a result of the proposed interventions and up to 0.9 °C lower daily area averaged temperature representing a 3% reduction compared to the original case as well as lower PET indices up to 29 °C at midday at specific locations under trees indicating relative improvement in pedestrian comfort during

periods of extreme thermal stress. Moreover, the typical building energy performance simulations indicate that the estimated ambient temperature reduction results in lower energy consumption for cooling up to 20% in contemporary climate conditions and up to 16% in future climate scenarios. Further studies are planned with installation of monitoring stations to observe and document microclimate development after the projects implementation.

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From Industrial District to Sustainable Eco-District: A Regeneration Framework for Scandicci Productive Area

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Abstract. Industrial districts are increasingly vulnerable to climate pressures, including heat accumulation, impermeable surfaces, and low ecological performance. This study presents a climate-responsive regeneration framework to enhance the resilience of productive areas, demonstrated through the Scandicci Fashion Cluster in Tuscany. By combining spatial analysis, on-site environmental assessment, and ENVI-met microclimatic simulations, the research identifies critical vulnerabilities and tests alternative design scenarios.

Results highlight severe heat stress, poor vegetation, and fragmented public spaces, which reduce thermal comfort and increase climate risks. To address these challenges, the study proposes nature-based design strategies—continuous green corridors, permeable bio-based surfaces, and climate-adaptive open-space redesigns—that enhance shading, evapotranspiration, and ecological connectivity. Simulations of post-intervention scenarios show measurable reductions in air temperature and significant improvements in microclimatic regulation and outdoor comfort.

This work demonstrates how climate-oriented design, informed by environmental modelling, can strengthen the resilience of industrial districts. The methodology offers a transferable, evidence-based framework for planners and policymakers aiming to integrate climate adaptation into productive urban landscapes.

Keywords: Industrial Districts · Climate Resilience · Regenerative Design · Nature-Based Solutions · Microclimate Modelling

1 Introduction

The transition toward a regenerative and circular built environment requires systemic transformations that involve not only individual buildings but also broader territorial systems such as industrial districts, production areas, and urban infrastructures. In this perspective, industrial areas represent strategic environments where environmental innovation, energy transition, and circular resource management can be implemented at district scale.

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Across Europe, the concept of industrial districts has progressively evolved from traditional manufacturing clusters toward more integrated models based on circular economy principles, energy efficiency, and industrial symbiosis. These approaches aim to optimize resource flows, promote energy sharing, and strengthen cooperation among firms and institutions in order to reduce environmental impacts and improve territorial competitiveness (Chertow, 2007; Gibbs & Deutz, 2007).

Industrial districts have historically played a central role in regional economic development, particularly in countries such as Italy where the district model has strongly shaped local production systems. According to the classical theory of industrial districts developed by Marshall (1920), the geographic concentration of firms facilitates specialization, knowledge exchange, and innovation processes. Later contributions emphasized the importance of networks, institutional frameworks, and innovation ecosystems in supporting territorial competitiveness (Porter, 1998).

In response to growing environmental pressures and climate policies, production systems are progressively evolving toward more sustainable and cooperative configurations. Within the Italian context, this transition has been addressed through the concept of Ecologically Equipped Industrial Areas (Aree Produttive Ecologicamente Attrezzate – APEA), introduced as a planning and governance tool aimed at improving environmental performance and resource efficiency within industrial districts. APEA promotes shared infrastructures, coordinated environmental management systems, and collective strategies for energy production, waste management, and water reuse. Despite their potential, the implementation of APEA has often faced challenges related to governance complexity, financial investment, and stakeholder coordination. Nevertheless, they represent an important framework for integrating sustainability principles into productive territories.

Several European experiences illustrate how industrial areas can transition toward more sustainable and circular models. The Kalundborg Eco-Industrial Park in Denmark represents one of the earliest and most successful examples of industrial symbiosis, where industries exchange energy, water, and by-products to reduce waste and resource consumption (Chertow, 2007).

Similarly, the regeneration of the post-industrial landscape of Essen (Germany), developed within the IBA Emscher Park program, demonstrates how former industrial sites can be transformed into ecological corridors and multifunctional urban spaces through environmental remediation and landscape regeneration. Another relevant example is the Gasverket redevelopment in Stockholm, where a former gas production plant has been converted into a sustainable mixed-use district integrating adaptive reuse of industrial heritage, energy-efficient buildings, and green infrastructures.

Within this broader European framework, the present research focuses on the Italian context and specifically on Tuscany, where policies related to the green economy and sustainable territorial development have promoted innovative approaches to the management and transformation of industrial areas. The study investigates how environmental analysis and microclimatic modelling can support the regeneration of productive districts through climate-responsive design strategies.

2 Case Study: The Scandicci Fashion Cluster

The case study focuses on the industrial district located in the municipality of Scandicci, within the metropolitan area of Florence in central Italy.

Originally characterized by dispersed artisanal workshops, the district has progressively evolved into a dense industrial fabric due to the growth of global luxury brands and the increasing concentration of production activities. This rapid expansion has resulted in the saturation of available land and the proliferation of large industrial buildings and parking areas.

Consequently, the district today presents several environmental vulnerabilities typical of consolidated productive areas: extensive asphalt and concrete surfaces, limited vegetation cover, and weak ecological connections with the surrounding landscape systems. The productive zone is also partially disconnected from the broader ecological network of the Florentine plain.

From a climatic perspective, the area experiences warm Mediterranean summers with average maximum temperatures around 31 °C in July. High solar radiation combined with extensive impermeable surfaces contributes to significant overheating of outdoor spaces and increased thermal stress during daytime working hours.

3 Methodology

The research adopts an integrated methodological framework combining spatial analysis, climatic assessment, and microclimatic simulation in order to evaluate the environmental performance of the study area and to support the development of regenerative design strategies. The methodological approach follows a sequential workflow structured as GIS-based spatial analysis, microclimatic simulation, design scenario development, according to an evidence-based design approach. This method allows design decisions to be directly informed by environmental data, spatial analysis, and quantitative evaluation of microclimatic performance.

The methodological workflow is structured into three main phases.

3.1 Environmental and Spatial Analysis (GIS-Based Assessment)

The first phase consists of a spatial and environmental analysis of the study area aimed at identifying the physical and ecological characteristics of the district and the main environmental vulnerabilities affecting its performance. Using GIS-based mapping, remote data, and field observations, several spatial layers were analyzed, including land use patterns, built morphology, surface materials, vegetation cover, and infrastructure networks.

Particular attention was devoted to the distribution of permeable and impermeable surfaces, the structure and continuity of green infrastructures, and the configuration of open and mobility spaces. This phase made it possible to identify critical environmental conditions such as the high percentage of sealed surfaces, the limited presence of tree canopies, and the fragmentation of ecological connections within the district.

The results of this phase were systematized through a set of thematic analytical sheets, which synthesize the spatial and environmental characteristics of the area through maps, diagrams, and quantitative indicators. The thematic sheets were organized around the following main topics:

- Land use and built morphology, including density, building layout, and spatial configuration of the industrial fabric;
- Surface materials and soil permeability, highlighting the distribution of impermeable surfaces and potential areas for depavement and soil regeneration;
- Green infrastructure and vegetation cover, analyzing the quantity, distribution, and connectivity of existing green spaces and tree systems;
- Mobility and infrastructure systems, including road hierarchy, parking areas, and pedestrian and cycling accessibility;
- Microclimatic vulnerability, identifying areas most exposed to heat accumulation and lack of shading.

These thematic analyses provided the analytical basis for the identification of critical zones and potential areas for environmental regeneration (Fig. 1).

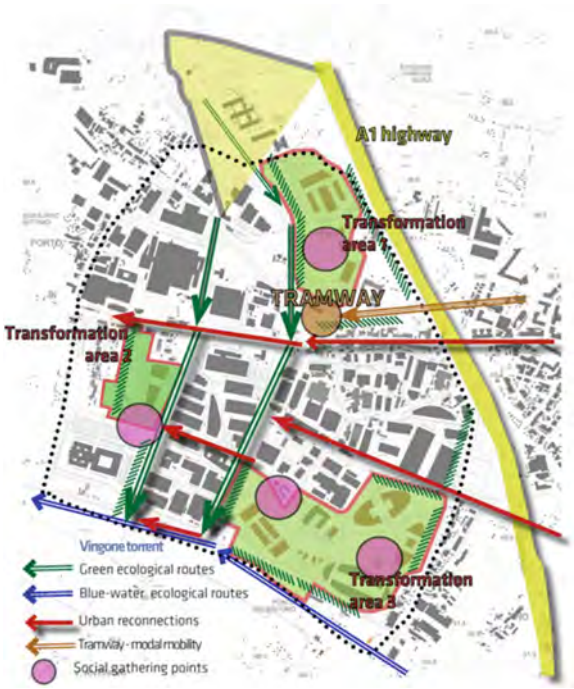


Fig. 1. Conceptual frameworks for the masterplan of intervention.

3.2 Microclimatic Assessment and Simulation

The second phase focuses on the evaluation of the local microclimatic conditions of the district. Historical climatic datasets and environmental indicators were analyzed to characterize the thermal behavior of the area, with particular attention to the most critical period of the day corresponding to working hours (9:00–19:00), which represents the time interval of greatest outdoor exposure for workers and users of the productive district.

Microclimatic simulations were conducted using ENVI-met, a three-dimensional numerical model widely used to simulate the interactions between urban surfaces, vegetation, atmosphere, and human thermal comfort (Bruse & Fleer, 1998). The model enables the simulation of processes such as radiation exchange, shading effects, evapotranspiration, airflow dynamics, and surface temperature variations at the neighborhood scale.

Through this phase, the baseline microclimatic conditions of the study area were reconstructed and analyzed, generating spatial outputs such as air temperature distribution, mean radiant temperature, and surface temperature patterns. These results were used to identify the most thermally critical areas and to support the definition of targeted environmental interventions.

3.3 Scenario Modeling and Evidence-Based Design Strategies

In the final phase, the results derived from the spatial analysis and microclimatic simulations were translated into a set of alternative design scenarios aimed at improving environmental performance and outdoor thermal comfort in compliance with the APEA regulations developed by the Tuscany Region (DPGR 2 December 2009, n. 74/R). Following an evidence-based design approach, the proposed interventions were directly informed by the analytical findings and targeted the most critical environmental conditions previously identified (Fig. 2).

The scenarios include strategies such as the increase of permeable surfaces through depavement interventions, the introduction of new tree systems and vegetated areas, the implementation of Nature-Based Solutions (NBS), and the application of cool materials to reduce surface temperatures. Additional strategies focus on strengthening the green infrastructure network and improving pedestrian and cycling accessibility within the district. Each scenario was simulated using ENVI-met in order to evaluate its potential microclimatic effects. Thermal comfort conditions were assessed using the Universal Thermal Climate Index (UTCI), which integrates air temperature, mean radiant temperature, wind speed, and relative humidity to estimate outdoor thermal stress (Fiala et al., 2012).The comparative analysis between the baseline configuration and the simulated scenarios allowed the identification of the most effective design strategies for mitigating the urban heat island effect, increasing soil permeability, and improving environmental and microclimatic conditions within the district. These results constitute the analytical and methodological foundation for the design scenarios of the research project, where the proposed regeneration strategies are spatially articulated and translated into project interventions for the case study area.

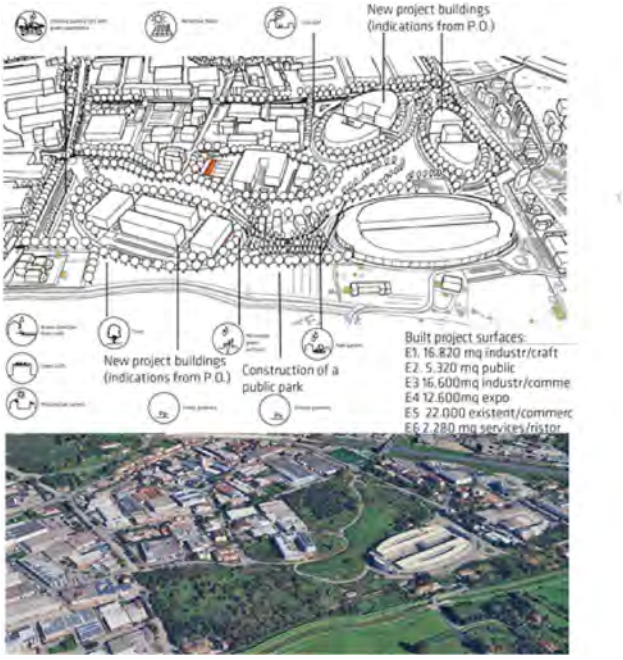


Fig. 2. Planned design interventions derived from scenario modeling and microclimatic analysis.

4 Regenerative Design Strategies

The environmental and microclimatic analyses conducted in the previous phases informed the development of a set of regenerative design strategies aimed at improving ecological performance and mitigating heat stress within the industrial district. Following an evidence-based design approach, the project integrates nature-based solutions and climate-responsive urban design strategies, which have been widely recognized as effective measures for mitigating urban heat island effects and improving outdoor environmental quality (Kabisch et al., 2017; Bowler et al., 2010).

The proposed interventions focus on three main components of the urban system: green infrastructure enhancement, surface material reconfiguration, and the redesign of mobility and open spaces. Vegetation cover is significantly increased through tree-lined streets, green corridors, and small woodland areas, strengthening the ecological network of the district while increasing shading and evapotranspiration processes. Tree planting is proposed along a large portion of the main road axes, contributing to the creation of continuous shaded routes and improving the environmental performance of mobility corridors (Fig. 3).

A second set of strategies involves the replacement of extensive asphalt surfaces with permeable and reflective materials, particularly in parking areas, pedestrian routes, and public open spaces. These interventions aim to reduce heat accumulation and improve stormwater infiltration capacity (Santamouris, 2013). Additional elements such as rain



Fig. 3. Planned design intervention for the hierarchical organization of mobility flows.

gardens, vegetated buffers, and permeable parking systems further enhance hydrological performance and microclimatic comfort within the district.

The environmental effectiveness of these strategies was evaluated through ENVI-met microclimatic simulations, comparing the existing configuration (ante operam) with the post-intervention scenario under typical summer conditions. The analysis focused on the most critical time interval between 12:00 and 14:00, when solar radiation and thermal stress reach their maximum levels.

Simulation results indicate a significant improvement in outdoor thermal conditions following the implementation of the proposed strategies. In the baseline scenario, the Universal Thermal Climate Index (UTCI) shows perceived temperatures ranging between 32 °C and 37 °C, corresponding to strong heat stress conditions across most of the district. In the post-intervention scenario, UTCI values decrease to approximately 26–31 °C in vegetated and shaded areas, indicating moderate heat stress levels and a noticeable improvement in thermal comfort.

The most significant reductions occur along mobility corridors and redesigned public spaces, where tree canopies and permeable materials effectively reduce solar exposure and surface heat storage. The combined cooling effects generated by shading, evapotranspiration, and increased soil permeability contribute to lowering both surface and air temperatures.

Overall, the results confirm the effectiveness of integrating nature-based solutions and climate-responsive urban design strategies in improving microclimatic conditions

within industrial districts. Beyond mitigating urban heat island effects, these interventions enhance ecological performance, hydrological resilience, and outdoor environmental quality, supporting the transition toward more sustainable and climate-adaptive productive landscapes.

Acknowledgments. This research builds upon the Master's thesis developed by Arch. David Darelli, which provided the analytical framework, design investigations and figures for the present study. The research activities were carried out in collaboration with the Municipality of Scandicci, which supported the work by providing planning documents, spatial data, and institutional input for the analysis of the study area and the development of the proposed scenarios.

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Urban Vegetation for Climate-Responsive Street Canyons: A Thermal Comfort Assessment

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Abstract. With the increasing impacts of climate change and urban densification, cities are exposed to extreme heat stress, associated with the Urban Heat Island effect. Many urban areas are characterised by street canyon geometries and limited vegetation, posing challenges to thermal comfort and urban resilience. Urban vegetation is increasingly recognised as a nature-based solution for mitigating urban heat. This study aims to quantify the relative contribution of vegetation shading and evapotranspiration to pedestrian thermal comfort under realistic climatic conditions. An unsteady Reynolds-averaged Navier–Stokes (URANS) Computational Fluid Dynamics (CFD) model is applied to investigate the impact of vegetation using a porous canopy representation that individually accounts for transpirational cooling, shading and vegetation effects on airflow and turbulence. The CFD flow field and conjugate heat transfer between solids and air are solved in a transient 3D framework, enabling time-resolved analysis of the thermal environment in the canyon over three consecutive days. Results show that evapotranspiration alone reduces in-canyon air temperature by up to about 1 °C, while shading further reduces the air temperature by another 1 °C and decreases ground temperature by up to 5 °C. The vegetation effects show Universal Thermal Climate Index (UTCI) reductions of up to 3.3 °C, indicating appreciable improvement in thermal comfort. Overall, evapotranspiration and shading are equally important contributors to air temperature reduction but shading stands out for its ground cooling effect. These findings may support the selection of appropriate vegetation species for climate-adaptive urban design under increasing thermal stress.

Keywords: urban microclimate · thermal comfort · heat stress mitigation · vegetation modeling · CFD

1 Introduction

More than half of the global population lives in urban areas, a proportion expected to increase further in the coming decades [1]. Urban areas are also responsible for the most of the energy consumption and greenhouse gas emissions [2], while climate change and urbanization increase urban heat stress through the Urban Heat Island (UHI) effect [1]. Urban vegetation has therefore been widely investigated as a nature-based solution for mitigating urban heat. Field observations from the Scaled Outdoor Measurement of Urban Climate and Health (SOMUCH) campaign [3, 4] have provided valuable insights

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into the interaction between trees, airflow and thermal conditions in street canyons. These experiments showed that trees can reduce wall and air temperatures primarily through shading effects [3], while more recent measurements highlighted the role of evapotranspiration [4].

To better understand the interaction between urban vegetation, airflow and thermal conditions, Computational Fluid Dynamics (CFD) has been used to investigate urban microclimates [5]. More recent studies have also incorporated vegetation transpiration in order to investigate the cooling potential of urban greenery [6, 7]. However the relative contribution of shading and evapotranspiration to the improvement of pedestrian-level thermal comfort within street canyons remains insufficiently quantified. This is the aim of the present study, using CFD simulations, based on the SOMUCH experimental configuration. Different vegetation modelling approaches are considered in order to isolate the aerodynamic, transpiration and shading effects of a tree canopy. The resulting changes in surface and air temperatures and pedestrian-level thermal comfort are evaluated using the Universal Thermal Climate Index (UTCI).

2 Methods

2.1 Numerical Model

URANS equations for incompressible, buoyant fluid flow and heat transfer are solved with an in-house finite volume CFD code with a Cartesian collocated grid arrangement. Pressure-velocity coupling is achieved with the SIMPLE algorithm, including appropriate corrections for face velocity interpolation. Details of the numerical framework and its validation are reported in previous studies [8, 9]. The model solves the continuity and momentum equations together with transport equations for turbulence kinetic energy and its dissipation, enthalpy and water-vapour specific humidity:

$$\frac{\partial(\rho\,\Phi)}{\partial t} + \nabla\cdot(\rho\,\mathrm{u}\,\Phi) = \nabla\cdot(\Gamma_\Phi\nabla\Phi) + S_\Phi \tag{1}$$

where the transported variable Φ corresponds to 1, (u), (v), (w), (k), (ε), ($C_p{\cdot}T$), (Y), respectively. Γ_Φ is the diffusion coefficient and ρ is the fluid density. S_Φ represents the source terms associated with each equation, including the pressure gradient, the additional molecular and turbulent diffusion and buoyancy, radiation, evaporation and turbulence production terms [8]. For the turbulence modeling the RNG k-ε model with wall functions is adopted. Density variations are modeled using the Boussinesq approximation, where buoyancy depends on both temperature and water vapour content, accounting for the effects of thermal expansion and humidity on air density.

2.2 Radiative Forcing: Solar and Thermal Radiation

The total incident solar radiation on an inclined surface is calculated using the ASHRAE model [10]. Solar declination and surface solar angles were computed according to United States Naval Observatory [11] and Clarke [12], respectively. Full methodology and implementation details are summarised in Barmpas et al. [8]. The total incident

shortwave solar radiation (I_t) is computed from the direct solar radiation (I_D), the sky diffuse solar radiation (I_{ds}) and the ground reflected radiation to the surface (I_{dg}) according to Eq. (2). The view factors F_{shad}, F_{sky}, F_{grd} represent shading, sky and ground contributions, respectively.

$$I_t = F_{shad}I_D + F_{sky}I_{ds} + F_{grd}I_{dg} \tag{2}$$

The total thermal radiation exchange is added to the source term in Eq. (1) when the temperature equation is solved ($\Phi = C_p \cdot T$). Shortwave radiation is multiplied with a local absorption factor (α), converting it into a thermal source. Longwave radiation is represented by thermal radiation exchange with the ground, sky and other surrounding surfaces. So, the total thermal radiation is:

$$Q = \left[\alpha I_t + e\sigma\left({T_s}^4 - {T_e}^4\right)\right]A_s, \quad {T_e}^4 = F_{sky}{T_{sky}}^4 + F_{grd}{T_{grd}}^4 + F_{lw}{T_s}^4 \tag{3}$$

where e is the surface emissivity, σ the Stefan-Boltzmann constant, A_s the surface area, T_s the surface temperature and F_{lw} the view factor toward neighboring objects. The sky temperature (T_{sky}) is computed using the model of Berdahl and Martin [13], which offers greater versatility, with separate formulas for clear and cloudy skies.

2.3 Case Configuration and Numerical Modelling.

SOMUCH is a series of outdoor experiments, investigating the environmental conditions within street canyons of different aspect ratios and thermal storage capacities [14]. The experimental campaign provides detailed information on the model geometry, the spatial and temporal distributions of in-canyon and ambient air and wall temperature as well as the downward shortwave radiation over the three days. These data were used to define the initial and boundary conditions and to validate the CFD results. The present CFD solver was applied to simulate the flow and thermal conditions in a street canyon of aspect ratio height to width AR = 1, corresponding to a case measured during SOMUCH. The simulations covered three consecutive days, during which the UTCI was evaluated. Another SOMUCH study [4] investigated the influence of vegetation on canyon temperature over a 24 h period, considering evapotranspiration and shading effects. In the present study, the same vegetation configuration as in that experiment is adopted in order to assess its impact on the UTCI, which is calculated using the standard operational procedure proposed by Bröde et al. [15].

The building models follow the SOMUCH configuration with dimensions of 0.5 × 0.5 × 1.2 m^3 and a wall thickness of 0.015 m. The computational domain is illustrated in Fig. 1 and the total number of cells in the domain was approximately 1.3 M with a minimum cell size <1.5 mm. A timestep of 20 s was adopted as suitable for the thermal comfort assessment. Points A and B are located at a height of 0.11 m in the scaled canyon (Fig. 1), corresponding to a pedestrian height of 1.65 m at full scale (1:15). Point A is sun-exposed, whereas point B is located beneath the tree canopy. Inlet velocity and turbulence kinetic energy profiles were prescribed from the wind tunnel measurements of Lin et al. [16], taken at the roof of the building upstream of the canyon. Following the specifications of Chen et al. [14], a reference velocity of U_{ref} = 0.5 m/s

was prescribed at a height of 2H above the ground, corresponding to a Reynolds number of $\mathrm{Re} = \frac{\rho \mathrm{H} u_{\mathrm{ref}}}{\nu} = 41{,}096$ and a bulk Richardson number $\mathrm{Ri_b} = 1.57$. The parameters for the solar and thermal radiation models were determined from the experimental data and site location (23.07° N, −113.38°E). The CFD framework for the non-vegetated canyon case has been extensively validated against the SOMUCH measurements for the three consecutive days considered in this study, including comparisons of the transient in-canyon air temperature, wall and ground temperature, although the results aren't shown here for brevity. In addition, the implemented humidity transport formulation was evaluated using a benchmark test case [17] involving evaporative cooling and moisture transport, showing satisfactory agreement with reference results.

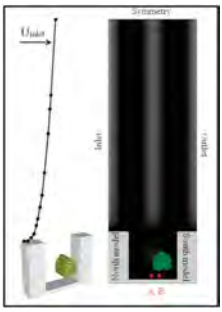


Fig. 1 CFD domain and computational mesh.

To evaluate the influence of vegetation, the cinnamomum kotoense tree used in the SOMUCH experiment by Wu et al. [4] was considered. The tree has an average Leaf Area Index (LAI) of 3.5 m^2/m^2, according to Li-cor LAI-2200 Plant Canopy Analyzer. The tree canopy geometry and dimensions were kept consistent with Wu et al. [4] and modeled as a cubic volume with a height and width of 0.5 m, while the trunk was neglected. Although in the experiment the vegetation was placed in the canyon center, in the CFD simulations it was placed near the windward wall (Fig. 1). The vegetated experimental case was used only to define the vegetation characteristics and not for direct comparison of UTCI values or flow fields. The present study evaluates the impact of introducing vegetation relative to the non-vegetated baseline simulations of the same three consecutive days. Positioning the tree near the sidewalk reflects common urban planting practices and allows the assessment of pedestrian thermal comfort at the canyon centre under both shaded and non-shaded conditions without relocating the main observation point.

2.4 Modelling the Influence of Vegetation on Airflow, Turbulence and Evaporative Cooling.

The influence of vegetation on the airflow and turbulence is achieved by the incorporation of the model of Sanz [18] through Eqs. (4),(5),(6):

$$S_{ui} = -\rho C_d \mathrm{LAD} U_i V \tag{4}$$

$$S_k = \rho C_d LAD\left(\beta_p V^3 - \beta_d Vk\right) \tag{5}$$

$$S_\varepsilon = \rho C_d LAD\frac{\varepsilon}{k}\left(C_{\varepsilon 4}\beta_p V^3 - C_{\varepsilon 5}\beta_d Vk\right) \tag{6}$$

where C_d is the leaf drag coefficient, LAD the leaf area density, U_i the velocity components of i direction, V the velocity magnitude. The coefficients are $\beta_p = 1.0$, $\beta_d = 5.1$, $C_{\varepsilon 4} = C_{\varepsilon 5} = 0.9$ [5]. The vegetation modelling approach has been validated against the study of Svensson and Häggkvist [19]. Wu et al. [4] measured the temporal mass loss of the plant and determined the tree latent heat flux (Q'_E) over a 24-h period. They also reported the 24-h downward shortwave radiation ($K'_\downarrow$). Based on these, the tree latent heat flux in the CFD study was calculated proportionally following Eq. (7):

$$Q_E(t) = \frac{Q'_E(t)K_\downarrow(t)}{K'_\downarrow(t)} \tag{7}$$

where $K_\downarrow$ is the measured downward shortwave radiation of the SOMUCH [14]. The volumetric cooling power P_c (W/m^3) is obtained from the latent heat flux Eq. (7) distributed over the vegetation height and introduced as a source term in the enthalpy equation following a similar approach to Gromke et al. [5]. In the present study, two extensions are introduced: the latent heat flux varies in time according to Eq. (7), and moisture transport is additionally solved through a humidity source term. In CFD simulations, the Beer-Lambert extinction law is used to represent the attenuation of solar radiation within the vegetation canopy [6, 7]. The shortwave radiative flux within a vegetation volume (I_{Dveg}) is calculated by Eq. (8), where θ_z denotes the solar zenith angle and β the extinction coefficient for shortwave radiation. This formulation allows surfaces shaded by the tree to still receive a reduced amount of direct solar radiation.

$$I_{Dveg} = I_D \exp\left(-\beta\frac{LAI}{\cos(\theta_z)}\right) \tag{8}$$

3 Results

Figure 2 illustrates the temperature distribution along the walls and ground at 12:00 on the first simulation day for the cases with and without vegetation. When vegetation is included (Fig. 2a), the tree shading reduces the ground temperature beneath the canopy by more than 5 °C, and the windward wall temperature in the region above the mid-height of the wall by 1–2 °C. The temperature lines indicate a slight cooling of the air passing through the tree canopy of approximately 1 °C, while the drag induced by the tree does not appear to significantly alter the velocity field.

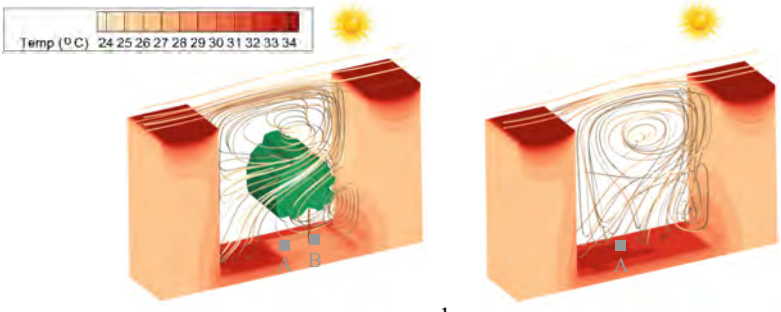


Fig. 2 Surface temperature contours and temperature coloured flow path lines at 12:00: (a) with and (b) without vegetation.

Additionally, the mean ground temperature and in-canyon air temperature for four selected hours (09:00, 12:00, 15:00 and 18:00) for each day are presented in Fig. 3. The mean ground temperature is calculated as the average value of the computational cells located at the ground surface. The in-canyon air temperature is computed at point A of Fig. 1. The contribution of vegetation is examined separately in order to distinguish the effects of shading from those associated with evapotranspiration. When only the evapotranspiration is considered (Drag + Transpiration), a slight increase in ground temperature is observed during the three simulated days, likely due to small modifications in the local flow pattern induced by the tree drag. In contrast, evapotranspiration reduces the in-canyon air temperature by up to 1 °C, particularly during the sunniest hours (12:00–15:00) of the first two days, while the effect is weaker during the cloudier third day. When the effect of shading is also included, the ground temperature is reduced by up to 5 °C during the first two days, which is also evident in Fig. 1. However, its influence on air temperature is more limited, with reductions below 1 °C compared to the case with only evapotranspiration and below 2 °C compared to the no-vegetation case.

Figure 4 illustrates the temporal variation of the UTCI at points A and B of Fig. 1. Even when only evapotranspiration is considered, UTCI decreases at point A, indicating the importance of air temperature reduction. The improvement becomes more pronounced when shading is included, reaching a maximum UTCI reduction of 3.3 °C at 15:00 on the first day and nearly resulting in a transition to a lower heat stress category, although point A remains unshaded. At point B, beneath the tree canopy and shaded for most of the day, thermal comfort is further improved, particularly between 12:00 and 14:00 when solar radiation is strongest, with UTCI values up to about 2 °C lower than at point A. After 17:00, the UTCI values at both points become similar, as solar radiation decreases. Overall, the tree presence improves thermal comfort even at sun-exposed locations, while shading beneath the canopy provides additional benefit.

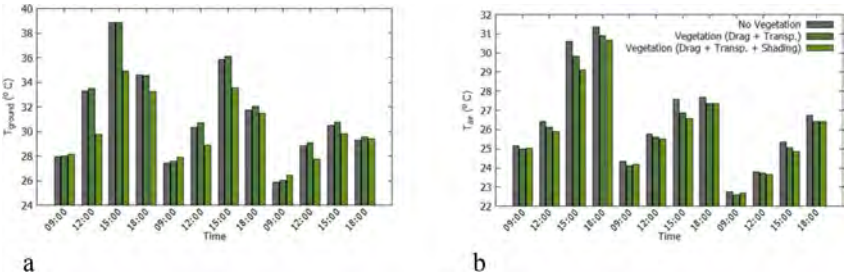


Fig. 3 Mean ground (a) and air (b) temperatures for the different vegetation cases.

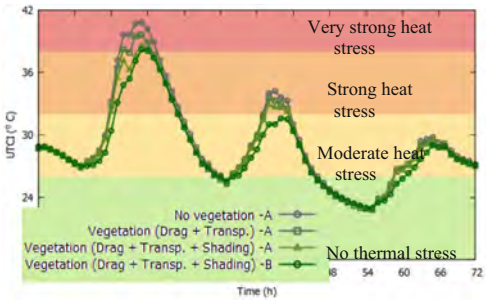


Fig. 4 Temporal variation of UTCI at points A and B for the different vegetation cases.

4 Conclusions

This study investigated the influence of urban vegetation on the thermal environment within a street canyon using CFD simulations based on the SOMUCH experimental configuration. Separate simulations were performed to isolate the aerodynamic, evapotranspiration and shading effects of a tree canopy. The results show that evapotranspiration alone reduces the in-canyon air temperature, while its impact on surface temperatures is limited. When shading is included, ground temperature decreases, particularly during periods of high solar radiation. The combined effect of shading and evapotranspiration improves thermal comfort, with UTCI reductions observed beneath the tree canopy and at sun-exposed locations. Evapotranspiration contributes mainly to air cooling, whereas shading has a stronger influence on surface temperature reduction and pedestrian thermal comfort. These findings may support climate-adaptive street design by highlighting the importance of canopy shading and evapotranspiration in tree selection and placement. The present study is limited to a single street canyon geometry and vegetation type, based on the SOMUCH setup. Therefore the quantitative results cannot be directly generalised to all urban environments, although the observed trends provide useful insight into vegetation cooling effects.

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Existing Public Spaces as Adaptive Systems: A Protocol-Based Approach to Climate Adaptation

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Abstract. Existing public spaces are increasingly subjected to climatic stressors, including extreme heat, heavy rainfall, and a prolonged period of environmental discomfort; nonetheless, their transformation is often attempted through fragmented interventions that lack systematic evaluation. Sharing the importance of working on integrated and complex approaches capable of holding together spatial, environmental, and socio-economic dimensions and centred on multiscale, the research explores the performance features linked to the key role that open spaces can assume within the urban network in managing technological and environmental issues. The paper proposes a systematic protocol for the climate-adaptive transformation of existing public spaces, framing them as dynamic environments that can be evaluated and enhanced throughout time. A critical review of climate resilience literature, public space performance frameworks, and environmental assessment methodologies is carried out to develop a multi-criteria protocol. The primary outcome of the research is the development of an operational and transferable protocol that approaches public space transformation as an iterative process instead of a one-time redesign. The paper concludes that conceptualising existing public spaces as adaptive systems establishes a solid foundation for responsible built environment practices, allowing climate adaptation strategies to be systematically implemented, assessed, and replicated across a diversity of urban contexts.

Keywords: climate adaptation · existing public spaces · adaptive systems · assessment protocol · urban resilience

1 Introduction: Climate Challenges and Trans-Scalar Approaches (C.F)

The environmental design of urban open spaces, in relation to the increasingly pressing challenges mainly linked to the climate crisis, remains a central theme in the field of environmental design. Since the 1950s, environmental design has addressed and contributed to providing concrete answers to critical issues related not only to energy saving

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and impact control but also to climate change. The challenge is broader and more complex, involving the building-open-space system, and should be addressed in terms of transitions, not only energy (towards clean and renewable energies) but also ecological and social.

In terms of prospects, it is strategic to work on research projects aimed not only at exploring technical aspects but also social and economic ones, without forgetting the importance of promoting best practices and reference models with strong demonstrative value. In line with what has already been tested in the field of *"tools for analysing, modelling, simulating and evaluating the environmental performance of open public spaces and the impact on them of the climate as the seasons change and also in emergencies"* [1].

The challenges we have faced in recent years have prompted us to adopt increasingly resilient behaviours and to define new norms and renewed balances.

This change in perspective can be extended to various fields of interest, and, in particular, for those involved in investigating the technological and environmental dimensions of transformation processes at different scales, it means focusing attention above all on the relationship between the natural and built environments, usability and well-being, infrastructure and innovation, taking into account both the priorities expressed by local communities and real needs, including in environmental terms [6].

The climate crisis has forced us to innovate and adapt. Concerning critical areas related to urban planning, this means considering the public environment as part of the solution to mitigate impacts, from rising temperatures to air quality and inequalities in the broadest sense. To build new balances and identify predictive scenarios, open spaces play a strategic role in the complex urban system. They act as drivers of human health [3] and interpret renewed models of liveability in the built environment.

This reasoning can be applied according to a transcalar approach, even in a wide-area perspective, in which the territory is conceived as a system of open spaces characterised by a high degree of flexibility and usable in different times and ways.

The concept of transcalarity highlights the *"ability to adopt different points of view, recognise connections and relationships, rationality and consonances that transcend time and space, connecting territories, actors and resources, and which encourages us to interpret the topological value of a context and the changing interactions between its social, physical, cultural, economic and environmental dimensions. The multiscalar and transscalar perspective enriches area-based approaches, allowing us to grasp those relationships (even immaterial and small-scale ones) on which to build the stability and sustainability of a regenerative process of urban space"* [2].

Finally, considering our cities as organisms and, therefore, not as linear but as circular systems should be the common denominator of transformative actions.

Sharing, among other things, the idea suggested by McDonough (2017) of the city as a "positive force", a scenario is configured in which working on urban environments means adopting strategies oriented not only to reducing negative impacts but, above all, to activating mechanisms to improve the quality of living.

2 Theoretical Framework (F.L.C)

The protocol developed in this paper is founded on three conceptual pillars: (1) the strategic significance of existing public open spaces as climate-critical urban infrastructure; (2) the application of adaptive systems thinking to the built environment; and (3) the primacy of measurable microclimatic performance indicators as the evaluative core of any climate adaptation assessment. Below, each pillar is developed.

2.1 Existing Public Open Spaces as Climate-Critical Infrastructure

The urban heat island effect is caused by an intricate mix of morphological and material factors, such as the replacement of vegetated permeable surfaces with impervious materials with low albedo, reduced sky view factors in canyon-like urban geometries that trap long-wave radiation, anthropogenic heat from transportation and buildings, and the loss of evapotranspiration as a latent heat sink [4, 5]. Existing public open spaces are where many of these drives meet. They are characterised by an excess of permeable hard surfaces, minimal tree canopy cover, and prolonged exposure to direct solar radiation. As a result, they are among the most thermally stressed environments in the built environment [7, 8]. Nonetheless, their spatial distribution throughout the city and accessibility to the whole metropolitan population position them structurally to operate as nodes of climate adaptation infrastructure [9, 10].

2.2 Adaptive Systems Thinking and the PDCA Protocol Lineage

The concept of public spaces as adaptable systems is based on urban resilience theory [11, 12], which defines adaptive systems by three key characteristics: their capacity to absorb disturbance, self-organise, and learn and adapt in response to experience. When applied to the built environment, this framing replaces the goal of a fixed design outcome with an ongoing cycle of adaptive management; a logic formalised in its most canonical operational form by the Plan-Do-Check-Act (PDCA) cycle, originally developed by Shewhart [13] and elaborated by Deming [14] in the context of industrial quality management.

The PDCA cycle formalises the principle that systemic improvement requires planned, repeating cycles of diagnosis, action, assessment, and adjustment, a logic operationalised in ISO 14001 [15] and in building performance evaluation frameworks [20, 27]. The protocol proposed in this paper is a domain-specific application of the proven iterative logic to existing public open spaces. Phase I (Diagnostic Assessment) operationalises Plan; Phase II (Intervention Typology Matching) operationalises Do; and Phase III (Integration and Iterative Evaluation) operationalises Check and Act, with the feedback loop completing the cycle and restarting Phase I.

Meerow and Newell [28] stated that urban resilience frameworks are only operationally useful if they include concrete assessment methods and indicators. The protocol given here responds to this demand, providing the procedural infrastructure for translating adaptive systems thinking into actual climate adaptation practice. Tyler and Moench [29] provided a framework for urban climate resilience based on repeated learning cycles, demonstrating the theoretical lineage's relevance to the urban adaptation context.

2.3 Primary Microclimatic Performance Metrics

The protocol's evaluative core is built on two measures. MRT, defined as the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body matches that in the actual enclosure [30], combines solar radiation, diffuse sky radiation, and long-wave emission from surrounding surfaces. Thorsson et al. [16] discovered that MRT is the most important driver of outdoor thermal comfort in sunny conditions, often exceeding ambient air temperature by 10 to 30° Celsius. Surface temperature complements MRT by capturing the thermal state of urban surfaces, which contribute to MRT via long-wave emission and local air temperature via convective heat transfer [17, 18]. Both metrics can be directly measured in field conditions with validated instruments and simulated using programs such as ENVI-met [19] and RayMan, facilitating pre- and post-implementation comparisons within a consistent methodological framework.

3 Research Methodology (F.L.C)

The paper is a literature-based framework development study. A critical integrative review was conducted across three bodies of literature: (1) urban heat and microclimate research, including the physical mechanisms of UHI, outdoor thermal comfort measurement and modelling, and the microclimatic effects of ecological and technological interventions; (2) public space performance frameworks that incorporate measurable environmental performance criteria; and (3) environmental assessment methodologies applied to urban infrastructure, including adaptive management protocols and post-occupancy evaluation frameworks.

Sources were included where they: (a) addressed measurable environmental performance outcomes; (b) engaged with existing or retrofitted urban environments; (c) demonstrated methodological transferability across diverse urban contexts; and (d) were peer-reviewed or produced by internationally recognised institutions.

Existing approaches address thermal performance only partially: Heat Vulnerability Indices [31] map demographic exposure at the city scale without engaging physical site design; thermal comfort studies [16, 22] measure how hot a space is without decomposing causal mechanisms; and public space frameworks [32, 33] treat comfort as one factor among many without systematic links to intervention categories. The protocol proposed here targets existing spaces rather than new-build environments, decomposes thermal vulnerability into causal dimensions explicitly linked to intervention categories, and structures transformation as a repeating adaptive cycle.

4 The Protocol: A Three-Phase Adaptive Framework (F.L.C)

The proposed protocol is divided into three consecutive and interdependent operational phases: (I) diagnostic assessment; (II) intervention typology matching; and (III) integration and iterative evaluation. Although presented sequentially, the protocol is fundamentally cyclical: Phase III's results feed back into Phase I, which approaches the transformation of existing public spaces as a continual, evidence-driven process rather than a one-time redesign event. Table 1 provides a summary of the three phases.

Phase II of the protocol operates by a fundamental instrument: the Eco-Technological Transformation Toolbox, which is a systematic, evidence-based inventory of ecological and technological interventions compiled through a parallel scoping review of the literature on the microclimatic performance of urban open space interventions.

The protocol, along with the toolbox, forms the methodological foundation of ongoing doctoral research on the climate-adaptive transformation of existing public open spaces. As part of this research, the complete three-phase protocol will be applied to a set of existing public open spaces in Budapest, Hungary, selected as case study sites. The protocol's operational validity will be tested, improved, and reported within the empirical context of the Budapest case studies, which represent a variety of existing public space typologies within a dense Central European urban fabric characterised by a continental climate with increasingly frequent and intense summer heat episodes.

Table 1. Overview of the three-phase adaptive transformation protocol.

Phase	Title	Core Question	Primary Methods	Output
Phase I	Diagnostic Assessment	What are the microclimatic vulnerabilities of this space under extreme heat?	Field measurement; ENVI-met simulation; morphological survey	Thermal Vulnerability Profile
Phase II	Intervention Typology Matching (via Toolbox)	Which interventions from the toolbox address the diagnosed vulnerabilities?	Toolbox consultation; matching matrix; ENVI-met scenario modelling	Calibrated Intervention Strategy
Phase III	Integration and Iterative Evaluation	Is performance improving? Does the strategy require adjustment?	Post-implementation monitoring, performance indicators, comparative analysis	Performance Report: Feedback to Phase I

4.1 Phase I: Diagnostic Assessment

Phase I provides the Thermal Vulnerability Profile, which determines all the following phases. Diagnosis must precede intervention selection [5, 7]; otherwise, resource allocation is arbitrary, and interventions risk being thermally ineffective or morphologically incompatible. Site characterisation measures the physical elements that are known to influence outdoor microclimate, such as the Sky View Factor [23], surface albedo and emissivity [17], vegetation Leaf Area Index [9], and diurnal shade distribution. Thermal vulnerability mapping combines field measurements (globe thermometry for MRT and infrared thermometry for surface temperature [16]) with ENVI-met simulation [19, 21], which includes at least one extreme heat episode campaign [24]. The Profile assesses

four vulnerability dimensions on a low, moderate, and high scale: radiation exposure [8], surface heat accumulation [17], evaporative cooling deficit [25], and thermal buffer discontinuity [10]. This composite signature determines which toolbox entries are activated in Phase II.

4.2 Phase II: Intervention Typology Matching

Phase II acts as the operational interface between the protocol and the Eco-Technological Transformation Toolbox. After completing Phase I, Phase II systematically consults the Toolbox, a structured, evidence-based inventory of ecological and technological interventions compiled through a parallel scoping review and selects those interventions most appropriate to the diagnosed vulnerability profile.

The Toolbox is organised along four parameters: (1) intervention type, ecological, technological, or hybrid; (2) vulnerability dimension addressed, cross-referenced to the Phase I scored matrix; (3) microclimatic performance evidence drawn from peer-reviewed literature; and (4) applicability conditions and feasibility requirements. Each of the four vulnerability dimensions cross-references a specific set of intervention categories within the Toolbox, with performance evidence and applicability conditions guiding selection.

The Toolbox offers multiple applicable interventions with different performance profiles and spatial requirements. Informed judgment guided by the Phase I Profile and Toolbox evidence is exercised to compose a site-specific Calibrated Intervention Strategy.

4.3 Phase III: Integration and Iterative Evaluation

Phase III assesses intervention performance against the Phase I baseline and determines if the calibrated intervention strategy met its predetermined objectives. In its full operational form, Phase III consists of post-construction field measurements replicating Phase I conditions, followed by a second campaign three years later to capture vegetation maturity impacts [26]. Four indicators are assessed against defined improvement thresholds: MRT Delta, with a target reduction of $\geq$5 °C under peak conditions [16]; Surface Temperature Delta, with a target reduction of $\geq$3 °C [17]; Thermal Comfort Duration, measured via PET or UTCI criteria with a target increase in comfortable hours [22]; and Shade Coverage Ratio during 10:00–16:00, with a target exceeding 30% [21]. Thresholds serve as indicative reference values calibrated against site-specific baseline conditions established in Phase I. The cycle continues for any dimension where thresholds are not met and concludes when all targets are achieved or when the documented strategy is transferable to comparable contexts.

Within this doctoral research, Phase III is enacted through simulation-based evaluation [7, 8, 21]: Toolbox-selected interventions are introduced into the ENVI-met baseline model calibrated against Phase I field measurements, and simulated outputs are compared against the Phase I baseline using the same four indicators. Where performance remains insufficient, the configuration is refined and remodelled, replicating the protocol's iterative logic within the simulation environment. This constitutes a proof-of-concept validation of the protocol across the Budapest case study sites.

5 Conclusion

Existing public open spaces are part of the most thermally vulnerable and of strategic significance for urban climate adaptation, but their transformation is largely reactive and fragmented. The protocol presented in the paper addresses this structural gap by presenting procedural logic based on adaptive systems theory and the PDCA iterative cycle, which connect accurate thermal diagnosis to evidence-based intervention selection and measurable performance evaluation. Its three-phase architecture, which is implemented through the Eco-Technological Transformation Toolbox, reframes public space transformation as a continual, evidence-based process rather than a one-time redesign event. The protocol is currently being applied to an existing public open spaces in Budapest, Hungary, as part of ongoing doctoral research. The framework presented here constitutes the methodological foundation for that empirical work and establishes a replicable procedural logic for climate adaptation strategies to be systematically implemented, assessed, and replicated across varied urban contexts.

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A Practical Application of Nature-Based Solutions: Parametric Framework for Local Adaptation and Replicability in European Cities

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Abstract. As climate change intensifies environmental pressures on cities, nature-based solutions (NbS) are increasingly promoted to enhance urban resilience, biodiversity, and human well-being. However, their adoption remains limited, partly due to the complexity of NbS systems and the lack of tools that clarify their contextual suitability across different urban morphologies and challenges. This research aims to facilitate informed decision-making by developing a replicable decision-support framework that links a catalogue of urban NbS archetypes, a set of common European urban morphologies, and recurring urban challenges. Assessment criteria are derived from existing Europe-wide NbS assessment frameworks and translated into qualitative suitability scores, enabling comparative evaluation across different NbS-morphology-challenge scenarios. The goal is to support the selection of suitable NbS combinations in specific urban forms to reduce the risk of maladaptation. This synergy analysis is translated into two complementary visualization-based tools designed to support different audiences. The first employs a set of 2D visualizations, including heatmaps and a Sankey diagram, to directly illustrate relationships between morphologies, NbS, and challenges. The second consists of a 3D parametric matrix developed in Grasshopper, enabling interactive testing of NbS feasibility through parametric logic. In both tools, users can select one or more elements to visualize compatible associations and potential synergies, thereby supporting qualitative and comparative assessment of NbS synergies across different urban morphologies and challenges. The framework is tested in the Mirafiori district of Turin and is designed to be adaptable to other European cities with comparable urban forms.

This work has been [partially] performed within the project ClimaGen – Climate-resilient reGeneration and renaturing for, by and with vulnerable neighbourhoods, striving towards net-zero, that has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101139637.

Keywords: Nature-based solutions · Urban morphologies · Urban challenges · Decision-support tool · NbS suitability

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1 Introduction

Cities are increasingly exposed to climate-related hazards such as extreme heat, drought, and intense precipitation events. In European urban regions, these phenomena are expected to intensify over the coming decades, amplifying environmental pressures and urban vulnerability [1].

Nature-based solutions (NbS) have emerged as promising strategies for addressing climate adaptation and disaster risk reduction simultaneously. By relying on ecosystem functions, NbS can mitigate climate risks while delivering multiple co-benefits such as urban cooling, stormwater management, and biodiversity [2, 3].

Despite their potential, NbS implementation in urban planning remains fragmented. Existing studies often evaluate individual NbS interventions or specific ecosystem services, while rarely considering how NbS interact with different urban forms and contextual challenges. Moreover, decision-support tools frequently prioritize environmental performance indicators while overlooking the influence of urban form on NbS feasibility and effectiveness [4–6].

This study originates from a master's thesis developed within the research activities of LINKS Foundation (Turin) and the European ClimaGen project (funded by the European Union's Horizon Europe, Innovation Actions programme under grant agreement No 101136112), which aim to develop a data-driven decision-support system supporting planners in identifying suitable NbS strategies and generating diverse scenarios [7].

Within this context, this research proposes a spatially sensitive framework for NbS selection that explicitly integrates urban morphology as a structural parameter. The framework links urban morphologies, environmental and social challenges, and NbS archetypes within a relational structure translated into a parametric visualization tool.

1.1 Research Objectives and Question

Thus, the proposed framework supports early-stage exploratory decision-making and improves the contextual suitability of NbS interventions.

To achieve this goal, the study is structured around the following objectives:

1. Identify and classify recurring European urban morphologies (UM) by defining a set of morphological typologies based on spatial characteristics and associated urban challenges (UC).
2. Identify and classify urban NbS archetypes (NbS) by analyzing their functions, spatial requirements, and potential benefits, including co-benefits and trade-offs.
3. Assess the qualitative relationships between NbS, UC, and UM through relational matrices describing spatial suitability (NbS-UM) and challenge-addressing capacity (NbS-UC).
4. Develop a replicable framework that integrates these relationships within a visualization environment capable of supporting NbS exploration at the early design stage.

Based on these objectives, the research addresses the following question:

How can urban morphology be systematically integrated as a structural parameter into a replicable framework that links them to NbS and challenges, while remaining adaptable to diverse European urban contexts?

2 Methodology

The research adopts a structured methodological workflow, combining conceptual analysis and tool development. The methodology consists of four main phases:

1. Literature review and definition of analytical categories, aimed at identifying the three core components of the framework: UM, UC, and NbS.
2. Development of the relational framework and visualization tool, integrating the three components through qualitative relational matrices describing spatial suitability and challenge-addressing capacity.
3. Contextual and spatial analysis of the case study area, used to interpret the outputs generated by the framework and assess their applicability in a real urban environment.
4. Design exploration, consisting of the spatial translation of selected NbS within the case study area to demonstrate the operational potential of the framework.

The approach builds on morphology-based conceptualizations of urban form [8, 9], focusing on physical characteristics, spatial configurations, and abstracting form from socio-cultural and land-use variations, thus enabling the identification of recurring morphological patterns that can be systematically related to environmental challenges and NbS implementation potential. This abstraction allows recurring morphological patterns to be identified across European cities while ensuring methodological transferability.

2.1 Literature Review

Screening and Selection of Analytical Categories. The three core analytical groups (UM, UC, NbS) at the basis of the framework were not defined ex-novo but rather systematically screened from existing literature and institutional frameworks.

As mentioned in the previous section, urban morphologies were selected based on morphometric factors derived from studies on recurring European urban forms [8–10]. The adopted approach therefore followed the abstraction of complex urban fabrics, specifying heights, forms, densities, relationship between constructed and open spaces. This facilitates transferability across European cities, comparison between climatic performances of recurring forms, and capacity to host certain NbS interventions. Five typologies were identified as representative of recurring urban fabrics: (1) High-rise housing: Isolated towers; (2) Mid-rise housing: Courtyard blocks; (3) Mid-rise housing: Linear slabs; (4) Low-rise housing: Dense village housing; (5) Low-rise housing: Isolated individual houses.

Urban challenges were selected from an internal research process developed alongside LINKS' research group. They were limited to those environmental and social pressures that can realistically be mitigated through NbS interventions. Twelve challenges were identified based on ecosystem service frameworks and climate-risk literature, including for example water scarcity, extreme heat, and limited access to quality green and recreational spaces [4, 11, 14, 16, 17].

Similarly, also NbS archetypes were screened from an internal catalogue developed alongside LINKS' research group and further refined through literature review [5, 6, 11]. From an initial set of 39 solutions, the current study utilizes eighteen NbS archetypes

compatible with urban environments, excluding larger territorial solutions (e.g., urban forest) or elements specific to a particular type of topography (e.g., living fascine).

This screening process ensured that the analytical categories were representative, transferable, and relevant to urban planning practice.

Qualitative Assessment of the Interactions. Two qualitative relational matrices were developed to assess interactions between the three analytical groups.

The first evaluates the spatial suitability of NbS within different urban morphologies (NbS-UM), considering physical constraints such as surface type, available space, and structural compatibility.

The second assesses the capacity of each NbS to address specific urban challenges (NbS-UC), based on evidence from scientific literature and European NbS best practices.

Both matrices use a qualitative scoring scale, informed by a comparative review of scientific literature, European case studies, and NbS catalogues [2, 5, 6, 12–17]:

- 0 – Not suitable;
- 1 – Partially suitable;
- 2 – Highly suitable.

The scoring process did not involve formal external expert validation. Instead, scores were derived through evidence synthesis from previously validated European assessment frameworks and research outputs, including previously developed study materials and institutional NbS assessment resources used within the broader ClimaGen research context.

The assessment should therefore be interpreted as a structured knowledge-informed screening process rather than a definitive performance evaluation, as the effectiveness of individual NbS depends on context-specific variables, such as local climatic conditions, ecological characteristics, and implementation practices. Accordingly, the framework is intended to support early-stage design exploration and inform subsequent context-specific analyses.

To allow the final generation of the tool, the Eq. (1) was adopted to combine the two matrices by using a conservative aggregation rule:

$$Final\ value = \min(NbS - UM, NbS - UC) \tag{1}$$

This ensures that an NbS is considered suitable only when both spatial compatibility and challenge relevance are satisfied.

By organizing these relationships within a relational parametric structure, the framework supports exploration of compatible NbS combinations, comparative evaluation of alternative strategies, and identification of potential synergies and trade-offs across different urban conditions, rather than prescribing a single optimal solution.

Existing NbS decision-support tools, such as impact evaluation frameworks and planning support systems [4–6], often focus on environmental performance assessment, ecosystem service quantification, or site-specific optimization. In contrast, the proposed framework is intended for earlier exploratory decision-making, introducing urban morphology as a structural screening parameter to support comparative identification of context-compatible NbS combinations rather than a single optimized intervention.

2.2 Tool Development

The following step consisted in the translation of the relational dataset into two different but complementary tools' options, to support users with a diverse level of technical expertise: (1) a 2D set of visualizations combining heatmaps and a Sankey diagram, and (2) a 3D parametric matrix generated in Grasshopper.

For the purposes of this paper, only the second visualization option – the 3D parametric matrix (Fig. 1) – is presented, as it provides the most comprehensive representation of the relational framework.

The three axes of the 3D system represent:

- X – Urban Morphologies (UM);
- Y – Nature-based Solutions archetypes (NbS);
- Z – Urban Challenges (UC).

Color encodes spatial suitability (NbS-UM relationship), while cube size represents the challenge-addressing capacity (NbS-UC relationship).

The parametric structure allows users to filter elements interactively, enabling exploration of NbS compatibility and potential creation of NbS pockets (or clusters) across different urban contexts.

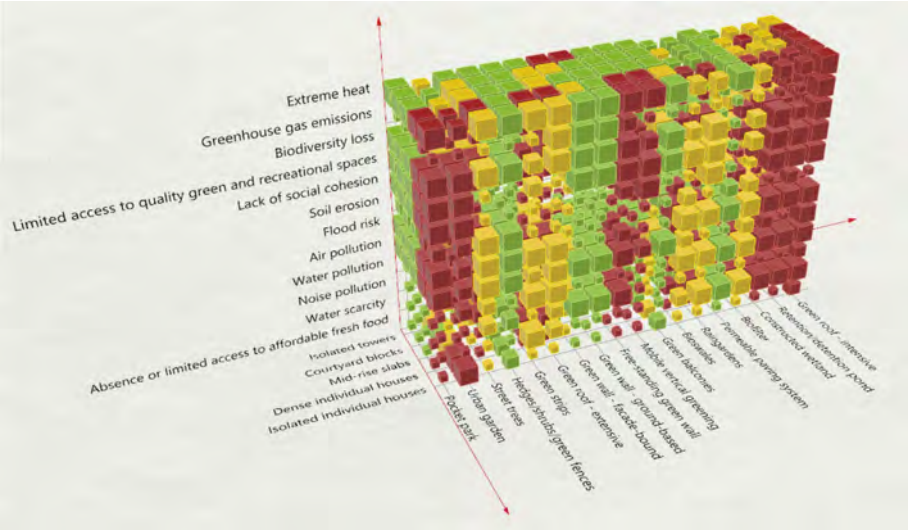


Fig. 1. 3D parametric matrix representing relationships between NbS (x), UM (y), and UC (z).

2.3 Data Analysis

The following step of the methodology saw the analysis and interpretation of the outputs generated by the matrix in relation to the specific conditions of the case study area. The tool enables users to select specific urban morphologies, environmental challenges, or

NbS archetypes to explore their interactions through iterative filtering and comparison. Through this process, users can identify NbS that are both spatially compatible with the selected urban morphology and capable of addressing the relevant environmental challenges that affect the project site.

The framework was tested and applied to the peripheral Mirafiori district in Turin, where the five urban morphology types were mapped, in order to validate the previously assessed selection. The analysis focused on the typology UM3 (Fig. 2) – mid-rise linear slab morphology – typical of post-war European social housing.

The analytical workflow therefore combines tool-based exploration with contextual site analyses, such as environmental, morphological, and in situ photographic evaluations, recognizing that the effectiveness of NbS strongly depends on local climatic, spatial, and socio-institutional conditions.

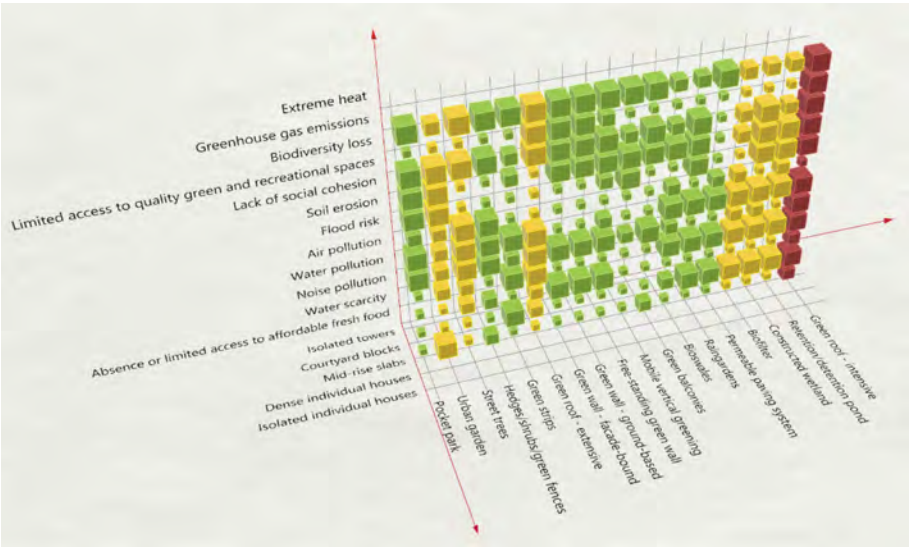


Fig. 2. Filtered view of the 3D matrix for UM3, showing compatible NbS archetypes and related urban challenges.

2.4 Design Application

Using the relational matrix, eight NbS archetypes were identified as particularly suitable for UM3 typology. These interventions were organized into two complementary NbS pockets addressing the main environmental challenges identified within the area, while mutually supporting each other's main functions:

- Water-sensitive NbS pocket, focusing on rainwater interception, collection, infiltration, and potential reuse through extensive green roofs, rain gardens, permeable pavements, and green strips.

- Urban cooling NbS pocket, combining street trees, pocket parks, ground-based green walls, and green hedges to mitigate heat stress, improve air quality, and introduce quality green spaces within the area.

The design exploration – showcased in the form of a masterplan proposal – illustrates how the relational 3D framework can support the translation of analytical outputs into spatial strategies without prescribing a single finite solution.

3 Discussion, Limitations, and Future Development

The proposed framework contributes to NbS planning research by introducing urban morphology as a structural parameter in NbS decision-making systems.

By organizing relationships between morphologies, challenges, and NbS through relational matrices, the framework shifts NbS planning from a solution-oriented perspective toward a more holistic, system-oriented approach.

Moreover, the parametric visualization tool facilitates the exploration of NbS compatibilities and supports the identification of NbS pockets capable of addressing multiple environmental and societal challenges simultaneously.

However, as the framework is intended as an early-stage exploratory support tool rather than a predictive optimization model, formal quantitative validation and benchmarking against established NbS decision-support systems, remain future development steps.

Future research could therefore address these limitations by comparing the framework with existing decision-support approaches, incorporating expert validation procedures, and integrating quantitative simulation-based environmental assessment, as well as economic feasibility of the solutions, governance constraints, and stakeholder participation, which are critical factors for successful NbS implementations.

Further developments could also include parametric automation to accelerate the selection of suitable NbS, as well as additional analytical layers, such as temporal scenarios that account for the progressive development of NbS effectiveness over time.

4 Conclusions

In conclusion, this research proposes a morphology-sensitive relational framework to support NbS selection in urban contexts. By linking the urban form, its challenges, and NbS archetypes within a parametric framework, the tool enables planners to explore context-appropriate NbS strategies and identify compatible NbS combinations.

The application to the Mirafiori district demonstrates how the framework can guide early-stage planning and design decisions while remaining transferable across different European urban contexts.

Future developments may bring the current framework toward a more advanced planning support tool to provide a more climate-responsive urban design.

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Adapting Urban Spaces for Healthier Environments

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Abstract. This paper addresses the imperative of adapting urban environments to climate change in accordance with European guidelines. Focusing on the requalification of urban open spaces, the study emphasizes the integration of social and technological dimensions to enhance environmental performance and public health outcomes. A comprehensive examination of materials and their potential combinations broaden the understanding of outdoor comfort and urban microclimates. The analysis investigates the intricate relationship between energy consumption, urban morphology, and bioclimatic comfort, particularly emphasizing the vulnerability of urban populations to adverse microclimatic conditions during elevated temperature periods. Consolidated cities have implemented effective strategies to mitigate heat exposure through structural and morphological interventions. This research underscores the necessity for urban systems to adapt proactively to climate-induced challenges, thereby fostering healthier living environments that promote the well-being of urban residents.

Keywords: Climate Change · Urban Microclimate · Public Health · Urban Participation · UHI Mitigation · Cooling Poverty

1 Introduction

Over recent decades, European cities have experienced a significant increase in the frequency and intensity of extreme weather and climate events. This trend is closely linked to rapid urbanisation, the progressive replacement of natural surfaces with impermeable materials such as asphalt and concrete and increasing building density [1, 2]. These transformations have altered the urban energy balance by modifying processes of heat absorption, storage and release, contributing to the intensification of the Urban Heat Island (UHI) phenomenon. As a result, urban areas often experience higher temperatures than surrounding peri-urban zones, with significant consequences for local microclimates, energy demand and residents' thermal comfort.

The implications of these processes extend beyond environmental impacts, affecting public health, urban ecosystem resilience and socio-economic stability. Heatwaves have become one of the most significant climate-related risk factors for the European population, causing tens of thousands of premature deaths in recent years [3]. Research shows

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that the impacts of urban overheating are unevenly distributed across cities and social groups. Exposure to climate risks and the capacity to adapt are strongly influenced by socio-economic conditions, characteristics of the built environment and access to urban resources. In this context, the theoretical framework of the social determinants of health, developed by Marmot and later applied to urban studies, is particularly relevant. According to this perspective, population health is shaped by everyday living conditions, the quality of residential environments and the opportunities provided by urban contexts [4].

Variables such as housing quality, domestic overcrowding, access to green spaces, mobility, accessibility to services, urban infrastructure and socio-economic status represent structural factors that influence living conditions and well-being. Cumulative exposure to environmental pressures, including air pollution, noise and urban overheating, can intensify existing vulnerabilities and generate health inequalities, particularly in dense urban areas [5–7].

At the same time, debates on climate change and building energy efficiency have introduced the concept of energy poverty, recently extended to the urban cooling dimension through the notion of cooling poverty (CP). According to Santamouris, energy vulnerability can be assessed through indicators including building thermal performance, access to cooling systems, household energy expenditure, indoor thermal comfort and the intensity of the urban heat island [2, 8]. Additional factors include the availability of passive cooling strategies such as natural ventilation, urban vegetation, shaded public spaces and high-reflectance materials.

Integrating the social determinants of health with energy vulnerability analysis allows the identification of urban areas where socio-economic disadvantage overlaps with environmental and climatic risks, producing higher exposure to urban overheating. However, despite extensive research on UHI and socio-environmental inequalities, a significant gap remains in understanding the interactions between urban morphology (UM), microclimate, socio-economic vulnerability and patterns of public space use, particularly in consolidated and densely built Mediterranean cities [9].

2 Objectives

This research investigated the relationships between UM, microclimate and socio-economic vulnerability in urban contexts characterised by high building density and limited green space. More specifically, it examined how urban overheating may intensify existing socio-environmental inequalities, producing forms of climate vulnerability that directly affect the health and well-being of urban populations.

The main objective was to develop an integrated approach to urban analysis capable of linking microclimatic indicators, morphological characteristics of the built environment and the social determinants of health, to identify strategies for mitigating the UHI and reducing CP. Within this perspective, the research sought to demonstrate how the design and regeneration of public spaces can serve as effective tools for improving urban microclimatic conditions, enhancing environmental comfort and strengthening climate equity.

A further objective was to assess the role of participatory processes in shaping strategies for urban climate adaptation. By directly involving residents and local stakeholders, the research explored the potential of co-design as a means of integrating scientific knowledge, social perceptions and everyday practices in the development of more effective and context-sensitive design solutions.

3 Conceptual Framework

This work brings together three research fields often treated separately: studies on urban microclimate and the UHI, research on environmental inequalities, the social determinants of health, and participatory practices focused on climate resilience.

The first field - urban climatology - studies the relationship between urban form, material characteristics and local microclimatic conditions. A large body of research has shown that the spatial layout of urban areas, high building density, the widespread use of impermeable surfaces and limited vegetation cover can alter local energy balances and increase heat accumulation in cities [1, 10]. These processes underlie the formation of the UHI, whereby urban areas experience significantly higher temperatures than surrounding rural zones, with important consequences for thermal comfort, urban liveability and the energy demand associated with cooling buildings [3, 12]. More recent studies show that both climate change and increasing urbanisation are intensifying these dynamics, making urban regeneration and green infrastructure ever more important in reducing urban overheating [13].

The second field concerns the social determinants of health, which highlight how socio-economic conditions, the built environment and the organisation of urban space shape people's well-being [5, 14]. From this perspective, factors such as housing quality, domestic overcrowding, access to green space, urban mobility and the availability of local services strongly influence people's exposure to environmental stress and their ability to adapt to climate change [11].

The third field relates to energy vulnerability and CP. These concepts describe conditions in which individuals or households lack the economic, technological or infrastructural resources required to maintain adequate thermal comfort during periods of extreme heat. Research has shown that energy vulnerability is not determined by income alone, but by the interaction between social conditions, the quality of the building stock, energy market dynamics and local climate conditions.

Together, these three fields provide a framework for understanding the relationship between the physical structure of urban space, the socio-economic conditions of local populations and ongoing climatic processes. In this perspective, the UHI is understood not only as an environmental or microclimatic issue, but also as a complex socio-environmental phenomenon shaped by both social inequality and changes in the built environment. This conceptual framework was translated into an analytical structure linking the physical components of the urban environment, microclimatic processes and the social determinants of health. This structure enables the interpretation of urban overheating as the result of the interaction between urban form, local climate conditions and the socio-economic vulnerabilities of resident populations. It also shows how these dynamics may lead to CP, while helping to identify adaptive and participatory urban design strategies (Table 1).

Table 1. Conceptual framework linking UM, climate exposure and CP.

Analytical Dimension	Key Variables	Processes and Impacts	Planning and Design Implications
Urban Morphology	Building density, street canyon geometry, urban materials, sky view factor, vegetation cover	Influences solar radiation absorption, heat storage, ventilation patterns and shading conditions within the urban fabric	Urban design strategies including vegetation increase, reflective materials, permeable surfaces, and improved urban ventilation
Urban Microclimate	Air temperature, surface temperature, radiation balance, wind speed, humidity	Formation and spatial variability of UHI; accumulation of heat in dense urban districts	Microclimate-sensitive planning; integration of green and blue infrastructures; mitigation of UHI; passive cooling strategies
Thermal Exposure	Outdoor thermal comfort indices (UTCI, PET), indoor overheating, duration of heat waves	Increased thermal stress for residents and higher energy demand for cooling systems	Climate-responsive design of public spaces, shading systems, and climate-adaptive street design
Social Determinants of Health	Housing quality, overcrowding, socio-economic status, access to green spaces, mobility and services	Unequal distribution of environmental risks and differentiated capacity to adapt to heat exposure	Inclusive planning policies addressing spatial inequalities and improving access to environmental resources
Cooling Poverty	Building thermal performance, access to cooling systems, household energy expenditure, passive cooling availability	Reduced capacity of vulnerable populations to maintain adequate indoor thermal comfort during extreme heat events	Integrated policies combining urban regeneration, energy efficiency improvements and social support mechanisms
Adaptive Urban Strategies	Urban greening, shading structures, reflective materials, participatory design processes	Reduction of local temperatures, improvement of thermal comfort and enhancement of social resilience	Co-design processes and participatory planning supporting climate-resilient neighbourhood regeneration

To support the interdisciplinary analysis of the case study, the research developed a set of indicators to describe the relationships between microclimatic conditions, the morphology of urban space, and the socio-environmental determinants of health. The indicators were selected from the scientific literature on urban climatology, urban health, and the assessment of energy and climate vulnerability in cities [1–3].

This system combines quantitative and qualitative data by linking physical and environmental parameters with social conditions and with the ways in which people use urban spaces. It therefore helps identify urban areas where intense UHI effects overlap with social and energy vulnerability, creating conditions of CP (Table 2).

Table 2. Indicators used for the integrated assessment of urban heat exposure and CP

Analytical Dimension	Indicators	Variables Observed	Measurement Tools / Data Sources
Microclimate	Air temperature; surface temperature; relative humidity; wind speed; solar radiation; thermal comfort indices (UTCI, PET)	UHI intensity; spatial variability of temperature; thermal stress conditions in public spaces	Portable weather stations; IR thermometers; anemometers; data loggers; microclimatic monitoring campaigns
Urban Morphology	Building density; building height; sky view factor; street canyon geometry; vegetation cover; surface materials	Heat accumulation patterns; shading conditions; ventilation corridors; permeability of the urban fabric	GIS spatial analysis (ArcGIS/QGIS); satellite imagery; photogrammetry; topographic surveys
Urban Materials	Albedo; emissivity; thermal capacity; permeability of surfaces	Heat storage capacity of pavements and buildings; surface overheating	Field surveys; infrared thermography; material databases; laboratory data
Social Determinants of Health	Housing quality; overcrowding; socio-economic status; accessibility to green spaces and services; urban mobility	Spatial distribution of vulnerability; unequal exposure to environmental risks	Census data; municipal databases; questionnaires; semi-structured interviews
Energy Vulnerability	Building thermal performance; access to cooling systems; household energy expenditure; indoor thermal comfort	Risk of overheating in dwellings; capacity of households to maintain thermal comfort during heat waves	Building surveys; energy statistics; household questionnaires

(*continued*)

Table 2. (*continued*)

Analytical Dimension	Indicators	Variables Observed	Measurement Tools / Data Sources
Participatory Processes	Perception of thermal comfort; use of public spaces; local knowledge on climate conditions	Identification of critical areas and adaptive practices used by residents	Participatory workshops; interviews; participant observation

4 Case Study: Via Galba, Ostiense District of Rome



Fig. 1. Project area

The morpho-typological configuration of the Via Galba neighbourhood, characterised by dense 12–14 storey residential blocks arranged around internal courtyards, with significant shading and limited ecological permeability, required an integrated approach capable of relating environmental, ecological, and human-use factors (Fig. 1).

To address this complexity, a multi-criteria matrix was developed, combining abiotic, soil, vegetation, and human-related components. This framework enabled a systemic evaluation of thermal comfort, ventilation, permeable surfaces, and ecological quality, while informing project scenarios focused on environmental adaptation, ecological connectivity, and the regeneration of public spaces.

The adopted design model integrated perceived urban well-being and public health through participatory design processes and community-oriented interventions, promoting more inclusive, climatically responsive, and resilient urban environments.

The design process helped to address social and environmental factors that may negatively affect the quality, liveability and identity of urban spaces, while also supporting social inclusion and civic awareness. The project also focused on strengthening trust between residents and urban space through observation, listening and interpretation of the critical issues and fragilities that contribute to feelings of insecurity.

Field measurements showed clear temperature differences across the area. Asphalt surfaces reached up to 48 °C and were 8–10 °C hotter than nearby green spaces. The morphological analysis also showed that the layout of the buildings limits airflow and increases heat build-up. The participatory process helped identify the main needs expressed by residents, such as shaded walking routes, cool places to sit, green paths and spaces for social interaction. The main proposals included more vegetation, materials with high solar reflectance, ventilation corridors and shaded resting areas (Fig. 2).

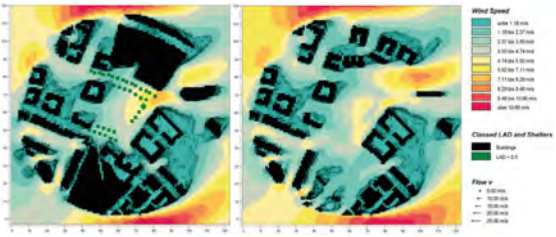


Fig. 2. ENVI-met simulations.

5 Results and Discussion

The Via Galba case showed that the combination of physical interventions and participatory processes can improve both microclimatic conditions and residents' perceived well-being. Field measurements revealed clear thermal differences across the area: asphalted surfaces reached up to 48 °C and were 8–10 °C warmer than nearby green spaces. Morphological analysis also showed that the urban layout and the limited presence of ventilation corridors favour heat build-up and intensify the UHI effect.

ENVI-met simulations indicated that targeted measures, including increased vegetation cover, high-albedo materials, shaded public spaces and ventilation corridors, can reduce surface and air temperatures and improve outdoor comfort according to UTCI and PET indices. These findings highlight the role of urban form and material properties in shaping local microclimatic conditions [1, 2].

The participatory process added an important social dimension to the study. Workshops and interviews helped identify the main needs expressed by residents, especially vulnerable groups such as children, older people and low-income households. The process also strengthened social cohesion, increased the sense of ownership of public spaces and supported the legitimacy of the proposed interventions. These results confirm that climate adaptation in urban areas is not only a technical matter, but also a social and institutional one [4]. Some limitations should also be noted. Long-term monitoring is needed to assess the durability of thermal benefits and the resilience of vegetation under changing climatic conditions. Seasonal and interannual variability may affect both the effectiveness of the interventions and the ways in which public spaces are used. In addition, the transfer of similar strategies to other urban contexts may require context-specific adaptations and suitable governance mechanisms (Fig. 3).



Fig. 3. The completed project.

6 Conclusions

The Via Galba case study confirms that integrating physical interventions with participatory planning is an effective way to mitigate the UHI effect and address CP in densely built urban areas. Measures such as increased vegetation, shaded public spaces, ventilation corridors and high-albedo materials can improve thermal comfort and urban liveability during periods of extreme heat. The study also shows that urban resilience should not be understood only in physical or environmental terms. It emerges from the interaction between spatial form, microclimate and community dynamics. In this respect, the direct involvement of residents played a key role in identifying local needs, supporting design choices and addressing both climatic and social inequalities. More broadly, the findings suggest that effective urban heat adaptation requires integrated strategies that combine environmental design, social inclusion and climate equity. To ensure long-term impact, these approaches must be supported by coordinated governance, continuous monitoring and adaptive management. In this sense, Via Galba offers a useful example of how more sustainable, inclusive and healthy urban environments can be developed through the joint action of communities, designers and institutions.

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Urban Streetscapes as Circular Infrastructures: The ClimaScapes Approach to Climate-Adaptive Regeneration

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Abstract. In the context of accelerating climate change and growing socio-environmental inequalities, circularity and climate adaptation are increasingly central to contemporary approaches to urban regeneration, particularly within the pervasive, everyday public infrastructures of streetscapes. Operating across scale, they play a strategic role in regenerative processes, by hosting multiple uses and actors, and offering continuous opportunities to integrate environmental, social, and spatial cycles within the urban fabric. Within this framework, the paper discusses EU-funded research developed by NatureCityLAB (UniBas) resulting in the design-oriented ClimaScapes platform, which addresses climate-adaptive urban regeneration through streetscape transformation. ClimaScapes is conceived as a digital knowledge infrastructure that systematically collects, analyses, and compares exemplary climate-adaptive streetscape projects worldwide, translating diverse practices into shared analytical and operational frameworks.

Grounded in design research, the platform structures knowledge between research and design, so as to enable a dialogue between different actors. The lessons learnt and the research methodology are then applied to the Italian city of Matera, a medium-sized Mediterranean city, where lessons learnt are critically reinterpreted rather than replicated. This application highlights the role of streetscapes as hybrid socio-spatial systems capable of addressing climatic vulnerability while reinforcing spatial quality and cultural continuity. The paper concludes by framing streetscape regeneration as a circular design process in which climate adaptation, knowledge transfer, and spatial transformation are mutually reinforcing, thus supporting regenerative urban practices that connect research, design, and governance within long-term, resilient urban transitions.

Keywords: Climate-adaptive urban regeneration · Streetscapes · Circular trans-formation · Design-oriented research · ClimaScapes

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1 Introduction: Streetscapes in the Climate and Circular Transitions

Climate change represents one of the most pressing challenges for contemporary cities, requiring profound transformations in how the urban environment is designed, governed, and inhabited. Urban areas are responsible for a large share of global greenhouse gas emissions while simultaneously being highly vulnerable to climate risks such as extreme heat, flooding, drought, and biodiversity loss (IPCC, 2022). These conditions reveal the limitations of modern urban paradigms that historically separate natural systems from built infrastructures and highlight the need to rethink urban design through integrative ecological approaches (Shahsavar, 2025).

In recent decades, the growing recognition of cities as socio-ecological systems has encouraged scholars and practitioners to reconsider the role of urban infrastructures within climate adaptation strategies. Traditional grey infrastructures designed primarily for technical performance, such as transport networks, drainage systems, and utility corridors, are increasingly being reinterpreted as hybrid spatial systems capable of integrating environmental processes with urban life (Meerow et al., 2016).

Among these infrastructures, streetscapes occupy a particularly significant position. Streets constitute one of the most extensive and continuous spatial networks within cities, structuring mobility while simultaneously functioning as social spaces and environmental interfaces. Their pervasive presence across urban territories makes them ideal sites for integrating climate-adaptive strategies capable of addressing multiple environmental challenges simultaneously.

Within this perspective, streetscapes may be conceptualized as circular infrastructures, spatial systems capable of supporting environmental cycles (such as water infiltration, energy regulation, and ecological connectivity) while simultaneously enabling social interactions and urban functions. Rather than operating as isolated technical systems, they function as integrative frameworks linking environmental processes with spatial design and governance structures.

The concept of circular urban infrastructures reflects broader transformations in contemporary urban theory, where cities are increasingly interpreted as dynamic systems characterized by interconnected flows of energy, water, materials, and information (Girardet, 2015). Within this frame, circularity also refers to resource-efficient streetscape transformation, including reduced soil sealing, reuse of existing materials where possible, and lifecycle-oriented maintenance strategies.

Within this conceptual and operational framework, the research developed by NatureCityLAB at the University of Basilicata[1] investigates the potential of streetscapes as key elements of Climate-Adaptive Nature-Based Urban Regeneration (CANBUR). Rather than treating nature-based solutions (NbS) as isolated technological devices,

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the research interprets them as spatial design components capable of shaping urban morphology and public space composition (Macaione et al., 2025).

The research develops a design-oriented methodology supported by the ClimaScapes digital and interactive platform that systematically collects exemplary streetscape projects integrating climate adaptation strategies in a broad Atlas.

Within this perspective, streetscapes become urban commons where ecological performance, spatial quality, and social interaction reinforce one another. Their transformation contributes not only to climate adaptation but also to broader regenerative urban processes that reconnect environmental systems with everyday urban life.

2 Streetscapes, Circularity, and Climate-Adaptive Urbanism

The transformation of streetscapes into climate-adaptive infrastructures emerges at the intersection of several debates within contemporary urban studies, which mainly revolve around the role of infrastructural landscapes in urban regeneration, the development of NbSs and blue-green infrastructures, and the emergence of circular urban systems. The first theoretical perspective concerns the reinterpretation of infrastructures through the lens of landscape urbanism (Corner, 2006). Within this framework, infrastructures are conceived as spatial frameworks capable of accommodating ecological processes and social activities across multiple scales. Within this perspective, streetscapes play a central role as they combine infrastructural, spatial, and social functions.

A second theoretical dimension concerns the development of NbSs and blue-green infrastructures as key strategies for climate adaptation. NbSs are defined as interventions inspired by natural processes that address societal challenges while providing environmental, social, and economic benefits (European Commission, 2021). Blue-green infrastructure systems operate as interconnected spatial networks that provide ecosystem services such as water regulation, climate mitigation, and biodiversity enhancement (Benedict and McMahon, 2006). When implemented within streetscapes, these infrastructures can transform urban corridors into ecological networks supporting water infiltration, vegetation growth, and microclimatic regulation.

A third conceptual dimension concerns the notion of circular urban systems. Circularity within urban contexts refers to the capacity of cities to reduce resource consumption, regenerate ecosystems, and close material and energy loops within urban metabolisms (Girardet, 2015). Within this perspective, streetscapes offer significant potential for supporting circular urban processes as they intersect multiple urban systems simultaneously. By integrating permeable surfaces, vegetation structures, and water management systems, streets can contribute to regulating urban metabolisms while improving spatial quality. Ultimately, they can be understood as hybrid socio-ecological infrastructures where environmental processes, spatial design, and everyday urban practices converge. Their transformation into climate-adaptive infrastructures represents an important step toward regenerative urban systems capable of addressing climate change while enhancing urban life.

3 Methodology: A Design-Oriented Approach

Within this research line, the CANBUR design-oriented methodological framework is developed, integrating analytical investigation with projective experimentation (Macaione et al., 2024). This approach draws from traditions of design research in architecture and urbanism where design is understood not only as a practice but also as a form of knowledge production (Frayling, 1993).

The methodology is structured around three complementary research phases: research *about* design, research *by* or *through* design, and research *for* design (Fig. 1).

The first phase, research *about* design, gathers knowledge from multiple disciplines, thus establishing the environmental and spatial parameters relevant to understand climate-adaptive streetscapes' design and their transformation's impact. The outcome of this phase are the analysis' tools and the ClimaScapes platform.

The second phase, Research *by* Design, investigates the specificities of the site through the analysis of its streetscapes, examining their spatial, environmental, and social conditions. This phase develops design guidelines tailored to the local context and results in the formulation of an Operational Methodology that guides the subsequent elaboration and implementation of the project.

The third phase, research *for* design, translates the extracted principles into experimental design scenarios applied to specific urban contexts. Through this phase, the research tests the adaptability of climate-adaptive strategies within different spatial and cultural conditions. The outcome of this phase is a design-oriented vision for a specific site, in this case for the borough of La Martella, in the city of Matera (Italy).

3.1 The ClimaScapes Platform

Within this methodological framework, the ClimaScapes platform functions as a digital and interactive knowledge infrastructure supporting the analysis, comparison, and dissemination of climate-adaptive streetscape projects.

ClimaScapes is conceived as a structured Atlas of climate-adaptive streetscape transformations, systematically collecting, analyzing, and comparing exemplary urban regeneration projects worldwide that integrate climate adaptation strategies through NbSs. Case studies are selected based on climatic relevance, grey typological diversity, and documented NbS implementation. Each is analysed through shared categories including vulnerabilities, NbS types, spatial devices, and architectural characters, according to the CANBUR methodology, following the five phases of (IPCC, 2022) general description and data collection; (Shahsavar, 2025) media collection (drawings, pictures, and multimedia contents); (Meerow et al., 2016) identification of vulnerabilities and potentialities; (Girardet, 2015) identification of NBS and their spatial implications; (Macaione et al., 2025) identification of architectural characters.

Through this process, many heterogeneous projects are translated into a common analytical language that allows cross-case comparison and the identification of transferable design principles. This analytical structure enables the platform to operate simultaneously as a research tool and as a design-support framework capable of informing future urban regeneration processes.

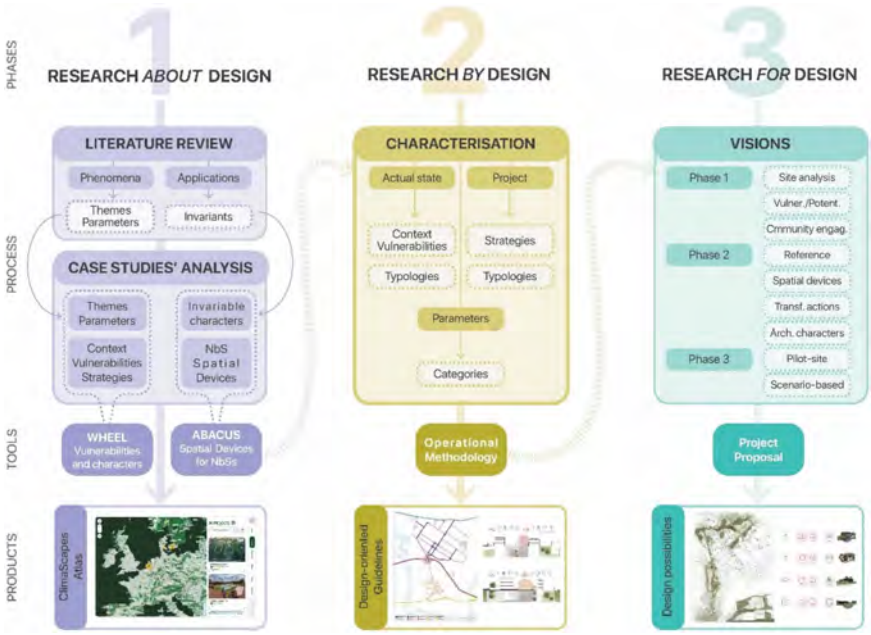


Fig. 1. CANBUR Methodology with phases, processes and outcomes (tools and products), as developed by the research (B. Andaloro, 2026, ©NatureCityLAB).

Moreover, a distinctive feature of the platform is its interactive geospatial interface, which allows users to explore case studies through an interactive map, where climate data layers are integrated.[2]

The interactive structure of the platform allows users to navigate across different scales, themes, and analytical categories. Projects can be explored through multiple entry points, including geographic location, climatic conditions, implemented NbSs, and spatial design strategies. This multi-scalar navigation facilitates comparative understanding between projects developed in diverse climatic and urban contexts and supports the identification of transferable design approaches.

Beyond its analytical function, the platform is conceived as a collaborative and evolving knowledge environment, which supports the dialogue between multiple actors involved in urban transformation processes, including researchers, municipalities, urban designers, planners, and community organizations.[3]

[2] The integration of georeferenced data from NASA geoportal allows to simultaneously visualise the streetscapes' locations together with other contextual and relevant information, such as temperature trends, precipitation patterns, and heat stress conditions.

[3] Municipalities and public authorities can use the platform as a reference system for developing climate-adaptive strategies and learning from international experiences. Researchers and students can contribute by enriching the Atlas with additional case studies and by testing methodological tools developed within the research framework. Finally, designers and practitioners can explore similar projects, share their own interventions, and contribute multimedia documentation to the platform's growing database.

In this sense, ClimaScapes acts as a dialogue tool bridging research and practice, enabling the exchange of knowledge across disciplinary and institutional boundaries.

3.2 Case Study Application: La Martella, Matera (Italy)

The CANBUR methodological framework is applied to the Italian city of Matera,[4] and specifically in the modern neighborhood La Martella, as an experimental case study.

Situated on a hill overlooking the surrounding landscape and strategically positioned in relation to nearby employment hubs, the neighborhood of La Martella represents a significant experiment in twentieth-century territorial planning, where architectural modernity was intertwined with rural traditions. Today La Martella can be interpreted as a composite territorial system formed by the historic residential nucleus and the adjacent industrial district, whose spatial and demographic dynamics have evolved unevenly over time. These two components exhibit markedly different morphologies and street patterns, ranging from orthogonal grid structures within the industrial zone to more articulated and irregular network configurations in the residential areas.

Adopting a research-by-design approach, the vulnerabilities are mapped and the transformative potential explored. In order to address the diversity of urban morphologies, a typological study of streetscapes has been developed as an operative analytical and design tool. Streetscapes are categorized according to the spatial sequence of elements composing their cross sections, as well as according to their dimensional relationships and spatial hierarchies. These typologies function as operative components towards a regeneration strategy, integrating ecological, social, and economic dimensions in a design guideline, capable of reactivating La Martella's public spaces.

Building upon this analytical framework, the project develops a strategic masterplan that reinterprets the ecological and hydrological dynamics of the site through the introduction of an integrated green-blue infrastructure through a continuous linear landscape system connecting the industrial area in the north with the historic borough in the south. Terraced landforms, infiltration basins, vegetated swales, and reforested slopes are introduced to mitigate surface runoff, enhance biodiversity, and generate accessible public spaces embedded within the landscape directly responding to runoff, heat-stress, and ecological fragmentation vulnerabilities previously identified.

The southern entrance to the neighborhood is reimagined as a productive and social threshold through the introduction of community gardens that reinforce local identity and collective stewardship addressing vulnerabilities related to social fragmentation and underused public edges, and reinterpreting Atlas examples where productive landscapes strengthen community stewardship. There, the connection between the industrial and residential sectors is redesigned as an active public spine integrating pedestrian and cycling infrastructures with spaces for temporary activities and markets mitigating accessibility and functional disconnection issues, informed by Atlas cases that transform mobility corridors into mixed-use public infrastructures

[4] Matera represents a medium-sized Mediterranean city characterized by significant climatic vulnerabilities, such as heat stress, water scarcity, and increasing frequency of extreme rainfall events.

A third intervention develops a system of green-blue corridors within the industrial district aimed at restoring latent ecological structures and improving environmental performance by reducing sealed surfaces and heat accumulatio; a fourth focuses on the reconfiguration of crossings and public facilities to enhance accessibility and spatial continuity responding to vulnerabilities related to unsafe pedestrian conditions and discontinuous public space.

Through these interventions, the lessons learnt from the ClimaScapes Atlas are adapted to the specific needs and applied to different locations. Specifically, NbSs are translated into concrete spatial devices, demonstrating how ecological processes can become generative elements in reshaping spatial hierarchies and fostering new socio-ecological relationships within the territory of La Martella.

4 Discussion: Streetscapes as Circular Urban Infrastructure

The research highlights the potential of streetscapes to operate as circular urban infrastructures capable of integrating environmental cycles with spatial design and social interaction. These interventions contribute to circularity not only ecologically but also materially, by extending infrastructure lifespans and reducing resource consumption. By incorporating NbSs within streetscape design, cities can transform conventional infrastructures into adaptive systems capable of regulating water flows, mitigating heat stress, and supporting biodiversity. At the same time, streets remain fundamental spaces for social interaction and urban life.

The ClimaScapes platform contributes to bridging the gap between research and practice by providing a shared analytical framework for climate-adaptive streetscape design. By translating diverse projects into comparable diagrams and analytical tools, it enables municipalities and designers to learn from existing experiences while adapting strategies to local contexts. For municipalities, this implies integrating climate-adaptive streetscape strategies into maintenance budgets, cross-departmental coordination, and long-term monitoring frameworks.

However, the research also highlights several challenges. Climate-adaptive streetscape transformations require coordination between multiple governance levels and stakeholders. Institutional capacity, funding mechanisms, and long-term maintenance strategies are essential for ensuring the effectiveness of these interventions.

Furthermore, the transferability of design strategies requires careful consideration of local climatic, cultural, and morphological conditions. Rather than replicating solutions, the ClimaScapes approach emphasizes reinterpretation and contextual adaptation.

5 Conclusion

This paper has explored the potential of streetscapes as circular infrastructures supporting climate-adaptive urban regeneration.

Through the integration of NbSs and blue-green infrastructures, streets can simultaneously address environmental challenges and improve public space quality. Their continuous presence within urban fabrics makes them strategic infrastructures for implementing climate adaptation strategies at multiple scales.

The research proposes a design-oriented methodological platform that combines comparative analysis with experimental design to develop transferable yet context-sensitive strategies for streetscape transformation.

The application to the city of Matera demonstrates how lessons derived from international case studies can be reinterpreted within Mediterranean contexts characterized by climatic vulnerability and historical urban fabrics.

Ultimately, streetscape regeneration should be understood as a circular design process in which environmental cycles, spatial transformation, and knowledge exchange reinforce one another. Through integrative approaches such as ClimaScapes, streetscapes can contribute to building resilient and regenerative urban environments capable of addressing the challenges of the climate transition.

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Stormwater Filtration Systems: Technologies, Implementation, Life Cycle Assessment, and Circularity Perspectives

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Abstract. Urbanization has significant effects on natural hydrological processes through preventing infiltration of rainwater as a consequence of high proportion of impervious surfaces in the urban environment and leading to high stormwater runoff. Besides, climate change also contributes to this. Stormwater runoff may result in floods and erosion problems as well as causing damage to urban infrastructure. Besides, it transports various type of pollutants -such as sediment, nutrient, polyaromatic hydrocarbons (PAHs), etc.- to the receiving surface waters. Thus, stormwater management is a critical component of sustainable urban development, enhancing urban resilience and sustainability. Stormwater filtration systems—including bioswales, constructed wetlands, sand and media filters, and emerging green infrastructure technologies—play a pivotal role in reducing pollutant loads, mitigating flooding, and enhancing water quality in the urban environment. In this study, current state-of-the-art on the stormwater filtration technologies, their implementation in the built environment, environmental sustainability of those systems focusing on previous Life Cycle Assessment (LCA) studies and circularity potential at different levels are reviewed with the aim of informing relevant stakeholders on the current practices and establishing a guide for future research on those systems toward more resilient urban water management.

Keywords: stormwater filtration · road runoff filtration · Life Cycle Assessment · circularity · sustainability · built environment

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1 Introduction

Increased frequency and severity of extreme weather events are one the consequences of climate change. Urban environment with large areas of impermeable surfaces prevent rainwater infiltration and increases the amount of surface runoff which may end up as floods, which contributes to the challenge of managing stormwater management. Also, various pollutants are transported through runoff to the surface waters. Stormwater filtration systems are essential elements of urban environment for reducing pollutant loads, mitigating flooding, and enhancing water quality. This study presents information on these systems, their implementation in the built environment, environmental sustainability and circularity potential based on a literature study of state-of-the-art. A non-systematic narrative literature review approach is used for the general information sections (Sects. 2 and 3), where relevant articles were identified through general academic database searches. For the part related to LCA, a systematic approach is used by searching the keywords 'stormwater' AND 'runoff' AND 'life cycle assessment' at Web of Science database and covering research papers for the last decade.

2 Overview of Stormwater Filtration Systems

2.1 Conventional Systems

Conventional stormwater filtration and treatment systems remain central to urban runoff management, especially in dense urban areas where space constraints, retrofit feasibility, and regulatory compliance often favor grey infrastructure. These systems - including sedimentation and detention facilities, sand and media filters, hydrodynamic separators, catch-basin inserts, and proprietary cartridge-based devices- physically remove pollutants through sedimentation, screening, filtration (Tran & Kang, 2013). Conventional stormwater systems provide hydraulic control and basic water quality improvement by removing suspended solids, particulate-bound phosphorus, metals, hydrocarbons, and other contaminants thorough settling and sedimentation. Advanced filtration systems, including engineered media and cartridge designs with materials such as perlite, zeolite, or activated alumina, combine multiple processes. Conventional stormwater systems remain effective for peak attenuation, solids capture, gross pollutant removal, and retrofit compatibility, especially when used in treatment trains combining sedimentation and filtration (Guerrero et al., 2020; Drapper & Hornbuckle, 2015). Yet, conventional systems alone often fall short in nutrient removal, multifunctionality, biodiversity, and circularity, prompting their integration with green infrastructure, reactive media, water reuse, and circular design strategies.

2.2 Green Infrastructure and Nature-Based Solutions

Green Infrastructure (GI) and Nature-Based Solutions (NbS) reposition stormwater management from conventional conveyance to decentralized, ecosystem-based retention, infiltration, and treatment providing environmental and societal co-benefits. GI as a strategically planned network of natural and semi-natural areas delivering a wide range

of ecosystem services, including water purification, climate regulation, and flood mitigation (European Commission, 2013). NbS use nature inspired solutions to tackle challenges such as climate change adaptation and water security (EEA, 2021). Typical GI and NbS used to stormwater filtration include bioswales, rain gardens, permeable pavements, green roofs, constructed wetlands, and floating treatment wetlands. These systems attenuate peak runoff and improve water quality through storage, infiltration, evapotranspiration, sedimentation, filtration, adsorption, plant uptake, and microbial degradation processes. Studies report effective removal of total suspended solids and heavy metals, while nitrogen and phosphorus removal varies depending on hydraulic loading, substrate composition, and vegetation type (Chatzimentor et al., 2020). System performance varies by soil or substrate properties, hydraulic residence time, climatic conditions, and maintenance practices. Engineered filter media usage and modular bioretention configurations have enhanced hydraulic performance and pollutant removal efficiency; however, operational constraints, including clogging and seasonal fluctuations, persist (Santos, 2025). Consequently, long-term functionality requires adequate pretreatment, effective vegetation management, and routine sediment removal, underscoring the importance of incorporating life-cycle considerations during design phase.

At urban scale, GI and NbS support multifunctional land use by integrating water management with biodiversity enhancement, urban heat island mitigation, recreational value, and carbon sequestration. European policy frameworks increasingly promote the integration of GI and NbS into spatial planning, urban regeneration, and climate adaptation strategies (European Commission, 2013; EEA, 2021). Compared to conventional grey infrastructure, these systems often match hydraulic performance while delivering broader ecosystem services and social benefits, though environmental sustainability must be accounting for embedded materials, land use, and maintenance.

2.3 Emerging and Innovative Technologies

NBS such as filter strips, riparian buffers, treatment wetlands, bioretention cells (rain gardens), dry swales, infiltration trenches, green roofs and permeable pavements are considered as systems treating stormwater through processes like filtration or adsorption (Oral et al., 2020). Grass swale, detention basin, retention pond and wetlands were identified as the mostly studied stormwater management NbS (Okaikue-Woodiet al., 2020). Biochars, lightweight aggregates, water treatment residues, and zeolites are widely used NbS materials that remove nutrients, heavy metals, organic contaminants, and bacteria; however, clogging remains a limitation, making pretreatment, flow control, and material choice critical for efficiency (Westholm, 2023). Okaikue-Woodi et al. (2020) revealed that organic filter media such as biochar, compost-, and woodchip-based materials can improve organic contaminant removal compared to inorganic media like sand, zeolite, or iron-based minerals. Media coatings with inorganic metal-oxides (iron hydr(oxide), manganese oxide, lanthanum) or organic composites (graphene oxide, polymer, surfactant) increase contaminant removal further. Waste treatment residues and fly ash were also proposed due to local availability, but, concerns over contaminant leaching limit their use. In contrast, inorganic media as perlite, vermiculite or iron/aluminium oxides could be preferred due to their high availability and durability. On the other hand, organic

filter media require regular replenishment despite improving sorption capacity. Nitrogen, a key stormwater contaminant, can cause eutrophication if untreated and is removed through complex biological processes. Biphasic or multilayer filtration systems with saturated and unsaturated zones, along with materials like biochar, activated carbon, and zeolite are recent innovations that enhance nitrogen removal (Zhang et al., 2021). Also, Zheng et al. (2025) highlights emerging technologies (i.e. smart sensors for system optimization), as ways to improve NbS efficiency.

3 Implementation of Stormwater Filtration Systems in the Built Environment

3.1 Building Integrated Systems

Conventional stormwater management, often referred to as grey infrastructure, directs runoff into local water bodies via drains, gutters, and underground pipes. However, pipe-based systems alone are often inadequate for urban stormwater management, prompting cities to explore alternative strategies that better support resilience goals (Prudencio et al., 2018). Sustainable Drainage Systems, Low Impact Development, Water-Sensitive Urban Design, Blue and Green Infrastructure (BGI), and Sponge City are examples of such stormwater management systems, which emerged with the aim of controlling runoff by boosting both water retention and infiltration (Bertrand-Krajewski, 2021). BGI adopts a forward-thinking approach by blending engineered systems with nature-based practices to achieve sustainable water management, either by protecting, restoring, or simulating natural processes within water cycles, thereby enhancing urban resilience and environmental quality (Andreucci, 2015). In urban areas, rooftops constitute a major share of impermeable surfaces, making them highly effective for building-level stormwater management. BGI, rain gardens, and infiltration basins are examples of NbS implemented at ground level to filter and retain stormwater (Chen & Gaspari, 2023). BGI applies ecosystem-based practices such as detention, storage, infiltration, and pollutant absorption to improve both stormwater quantity and quality. Rain gardens act as mini-reservoirs, absorbing runoff and removing pollutants like pathogens, nutrients, organic materials, and heavy metals. Infiltration basins capture, temporarily hold, and gradually filter runoff, thereby reducing surface flow and pollutant load. These ground-level NbS are typically planned at neighbourhood scale, to enhance urban sustainability and resilience (Oral, et al., 2020). Research also indicates that combining multiple NbS measures usually produces better outcomes than applying them separately. However, most studies are discipline specific - focused on fields like architecture, landscape design, agronomy, engineering, or meteorology- and rarely adopting a holistic perspective that accounts for interactions between built environments and natural systems, especially within urban contexts (Alves, et al., 2020). By integrating conventional systems with BGI, cities can adopt adaptive, cost-effective, and scalable solutions for urban flood resilience (Ershad Sarabi et al., 2019).

3.2 Public-Space and Landscape Elements

Public-space and landscape elements are highly visible and multifunctional domains which are embedded into streetscapes, parks, plazas, parking areas, road verges, and other

open urban spaces rather than hidden in drainage networks. They provide runoff capture and pollutant removal but also have capacity to reshape urban space as hydrologically active infrastructure by combining hydraulic, environmental, and spatial functions. The most relevant stormwater filtration elements include bioswales, vegetated swales, rain gardens, bioretention planters, permeable pavements, retention and detention landscape basins, constructed wetlands (Ekka et al., 2021; Sambito et al., 2021).

3.3 District-Scale Infrastructure

As climate risks intensify, conventional grey infrastructure is becoming less reliable, prompting cities to adopt adaptable, sustainable, and cost-efficient blue-green solutions, underpinned by EU policies and green initiatives. District-scale solutions include individual buildings, neighbourhoods, or grey infrastructure, while larger-scale interventions encompass city-wide stormwater systems or flood barriers (ARUP, 2014). District- and city-scale BGI improve stormwater management, biodiversity, and community resilience, while hybrid grey-green-blue systems combine engineered and natural features to address extreme events (Kapetas and Fenner, 2020). Beyond flood control, these systems also mitigate urban heat, improve well-being, and support biodiversity.

4 Environmental Sustainability Assessment Using LCA

Life Cycle Assessment (LCA) is a quantitative method used to evaluate the environmental impacts of products, systems, and services, and is widely used to assess the environmental performance of stormwater filtration systems. In most cases, a cradle-to-grave approach is applied, covering material production, construction/installation, operation, and end-of-life (EoL) (i.e. Mohamed et al., 2023), while some cases only focus on the processes up to installation/operation (i.e. O'Sullivan et al., 2015) (Fig. 1).



Fig. 1. Literature on LCA of stormwater management systems (arrows: system boundaries; Icons: system type, functional unit, environmental hotspots; NBS: Nature-Based Solution; BPM: Best Management Practice; EoL: End-of-Life) (Icons are from www.flaticon.com)

With a general view, production of construction materials - due to its high energy and resource demand - and the construction phase, including excavation, transportation and installation are identified as the environmental hotspots (O'Sullivan et al., 2015; Faragó et al., 2019; Mohamed et al., 2023). In contrast, GI & NbS offer advantages through lower material requirements and ecosystem service contributions that can offset life cycle burdens (i.e. carbon sequestration by the vegetation) (i.e. Petit-Boix et al., 2017; Jato-Espino et al., 2022) (Fig. 1).

5 Circularity Perspectives

GI & NbS applied to stormwater filtration have water circularity potential, while conventional stormwater filtration systems transferring runoff quickly and discharge. By usage of GI & NbS, runoff flow is slowed, retained and treated locally, which makes the beneficial reuse of water for non-potable purposes (i.e. agriculture, cooling, etc.) possible. Thus, consumptive water use and waste externalities (i.e. energy required for operation) are designed out; resources are kept in use and natural capital is preserved (i.e. pollution prevention, minimum disruption to natural water, etc.) (Deksissa et al., 2021). Material circularity is also another aspect provided by stormwater filtration systems. Some of the components of stormwater filtration systems can be manufactured using recycled materials reducing the demand for virgin materials with an important amount of avoided burdens. Usage of construction and demolition waste, industrial by-products (fly ash, slag), and municipal waste for permeable pavement production (Vachasiddha et al., 2024); usage of sludge-derived activated carbon as filter material in biofilters (Mohamed et al., 2023); usage of biochar produced from waste biomass as filter material (Ulrich et al., 2024); usage of recycled plastic for some components (O'Sullivan et al., 2015) are some examples of this. Recycling of some components of those systems at the end of their useful lifetime is considered (i.e. onsite reuse on rain garden media (Flynn & Traver, 2013)), which is also an action contributing to material circularity (Faragò et al., 2019). However, this approach generally is not applied for filter materials, and they are generally disposed of as waste, which transforms the filter system into a process that has only changed the phase in which the pollutant is located, but has not eliminated the concept of waste. Also, research on applying design by circularity principles and circularity of stormwater filtration systems is limited.

6 Conclusion

Stormwater filtration systems are key components of built environment, providing runoff management, supporting water circularity, and improving water quality. They can be implemented at building, public-space, or district scales. LCA studies suggest that GI & NbS generally reduce downstream infrastructure burdens and provide co-benefits, compared to the conventional stormwater filtration systems. While both conventional and GI & NbS may have circularity potential in terms of raw materials and EoL practices, filter material is typically being disposed of as waste rather than reused. As a result, studies incorporating circular design principles and circularity assessment in stormwater filtration systems remain limited and require further developed.

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Rebuilding War-Torn Cities with Frontier Science-from Bottom-up Approaches to Sustained Resilience

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Abstract. Post-war reconstruction has historically prioritized rapid physical rebuilding and economic interests, often neglecting long-term resilience, social equity, and environmental sustainability. This paper introduces a transformative, multidisciplinary framework designed to reshape recovery in conflict-affected cities - placing communities, circularity, and sustainability at its core toward sustained resilience. Grounded in cutting-edge science and aligned with the Sustainable Development Goals and planetary boundaries, the framework operates across three temporal phases—anticipatory adaptation, emergency response, and post-crisis recovery—integrating key city domains and output: society, economy, and natural & built environment. We emphasize the role of digital innovation, such as AI, digital twins, and participatory platforms, in enabling agile, inclusive, and evidence-based reconstruction. AI-driven damage assessments, digital twins, and participatory platforms support evidence-based and inclusive reconstruction in inaccessible conflict settings. This approach contrasts with fragmented, top-down models, advocating instead for context-driven strategies that reconcile urgent humanitarian needs with long-term regenerative outcomes. By bridging gaps in existing disaster management methodologies, this framework offers a scalable pathway to resilient, sustainable, and socially just recovery.

Keywords: Post-war Reconstruction · Circularity · Resilience · Sustainability · Digital Innovation · Community Engagement

1 Introduction

Armed conflicts devastate societies in ways that extend far beyond physical destruction. Unlike climate-induced or natural disasters - which are typically acute and time-bound - wars produce systemic, protracted, and politically entangled crises that paralyze governance and dismantle the core systems sustaining urban life [1]. The destruction of infrastructure in contexts such as Ukraine, Gaza, and Syria has turned recovery into one

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of the most complex challenges of our time. While natural disasters often trigger structured international responses, post-war reconstruction unfolds in fractured environments characterized by deep social scars, institutional erosion, and a lack of unified recovery mandates.

Despite global investments in resilience, rebuilding remains overwhelmingly slow, fragmented, and reactive. The war in Ukraine alone has resulted in infrastructure losses exceeding $587 billion [2], yet systematic, future-oriented recovery strategies remain elusive. Similar stagnation is evident in Iraq and Syria, revealing structural weaknesses in current frameworks that often prioritize geopolitical agendas over social equity and scientific rigor. Rebuilding in these contexts requires a paradigm shift from asset-focused reconstruction to systems-based restoration. In war-torn regions, critical infrastructure functions as the backbone of social cohesion and economic survival; its destruction immobilizes daily life [3]. Current frameworks remain predominantly reactive and underutilize emerging technologies due to fragmented data systems. Moreover, the "brain drain" of technical expertise and rigid donor-driven financing further entrench exclusionary, top-down models.

This paper proposes a comprehensive, science-based recovery framework aligned with the UN Sustainable Development Goals (SDGs) [4]. We advocate for a tiered strategy that integrates resilience prior to conflict, supports emergency response and mitigation during conflict and leverages data-driven governance for post-conflict restoration. By bridging the gaps between infrastructure science, digital innovation, and community engagement, this study outlines a scalable pathway to reinstate not only functionality but also dignity and resilience in post-conflict cities.

Methodologically, the framework was developed through an interdisciplinary synthesis of post-conflict recovery, critical infrastructure resilience, socio-technical urban systems, circularity, and digital urban governance literature. The synthesis was structured around three analytical steps: first, identifying how conflict disruption differs from natural-hazard recovery; second, mapping reconstruction needs across society, economy, and the natural and built environment; and third, translating these domains into a phase-based recovery framework supported by digital tools, participatory governance, and circularity principles. The framework is conceptual but operationally oriented, supporting future case-based validation and decision-support development.

2 Redefining Recovery: A Multidimensional Framework

Current post-war recovery efforts are frequently fragmented, reacting to crises rather than anticipating them. While frameworks like the World Bank's Rapid Damage and Needs Assessment (RDNA) provide essential snapshots of physical damage, they often overlook the systemic, spatiotemporal interdependencies of urban life. Furthermore, conventional disaster risk management methodologies often fail to account for the unique volatility, uncertainty and cascading effects associated with armed conflict.

2.1 Beyond Natural Disasters: the Distinct Nature of Post-conflict Recovery

The World Economic Forum's Global Risks Report 2026 [5] underscores the rising complexity of modern crises, driven by interdependent risks such as geopolitical instability and resource scarcity. This necessitates distinguishing natural and conflict-induced hazards, which affect cities and critical infrastructure differently.

Unlike natural hazards - such as earthquakes or floods - which are typically acute, time-bound events following predictable attenuation laws, armed conflicts are protracted, anthropogenic, and deliberate. Natural disasters allow for structured recovery following a single shock; conversely, conflicts produce sustained, cumulative destruction where infrastructure is not damaged by environmental forces but is often intentionally targeted to disrupt societal function [3, 6]. This leads to distinct damage patterns: while natural hazards often result in predictable structural failures concentrated in specific zones, conflict damage is sporadic yet extensive, characterized by class imbalances where completely destroyed assets may sit alongside untouched areas.

Crucially, the operational context for recovery differs in three key areas [4]:

(i) **Temporal Uncertainty and Lag Time:** Recovery from natural disasters typically benefits from shorter lag times, with international aid mobilized quickly and reconstruction driven by national priorities. In contrast, post-conflict reconstruction faces substantially longer delays—often years—due to security constraints, political instability, and the potential rejection or blockage of foreign aid [7].

(ii) **Data Accessibility:** While data for natural disaster response (traffic flows, inspection records) remains largely accessible, conflict zones suffer from severe information blackouts and widespread infrastructure disruption across multiple locations. Security risks limit on-site inspections, necessitate greater reliance on remote sensing and open-source intelligence. These challenges are further compounded by data protection concerns, disrupted communication systems, and loss of institutional capacity.

(iii) **Functional Shifts and Repurposing:** Perhaps most significantly, post-war recovery cannot simply aim for "return to normal". The demographic reality of war—mass displacement and "brain drain" - fundamentally alters the functional demand on infrastructure. Recovery strategies must therefore incorporate the emergent use of assets, addressing reduced capacity needs, altered mobility patterns, and new demands in specific areas. While recovery following natural disasters typically aims to restore full operating capability, recovery in conflict-affected settings often needs to prioritize a minimum sustainable capability – namely, performance levels that can be maintained using available local resources - before progressively scaling up [1, 3].

Consequently, while resilience to natural hazards focuses on resisting environmental loads, conflict resilience requires distinct proactive measures. These include decentralized infrastructure (e.g., microgrids), dual-use facilities (e.g., underground shelters), and modular systems that allow for interchangeable components - strategies currently underutilized in standard building codes. To address these structural weaknesses, we propose a transformative, science-based framework (see Fig. 1) designed to operationalize the city as a dynamic system of systems [8]. It is structured across three temporal phases -

anticipatory adaptation (before), emergency response (during), and post-crisis recovery (after) - and operates through the integration of three core domains: society, economy, and the natural & built environment.

2.2 From Reactive Rebuilding to Proactive Resilience and Sustainability

The traditional "build back better" narrative often traps cities in a reactive cycle. Our framework advocates for a shift toward proactive, threat-agnostic planning [9]. This means interventions made before or during conflict are designed with dual utility—serving immediate protective functions while laying the groundwork for peacetime regeneration. Despite these growing challenges, existing recovery frameworks often fall short. Current approaches overemphasize risk assessment while neglecting the balance between immediate restoration needs and long-term sustainability. Infrastructure recovery models tend to focus on restoring pre-disaster conditions, a reactive approach that perpetuates cycles of damage and reconstruction, deepening social and economic vulnerabilities [10].

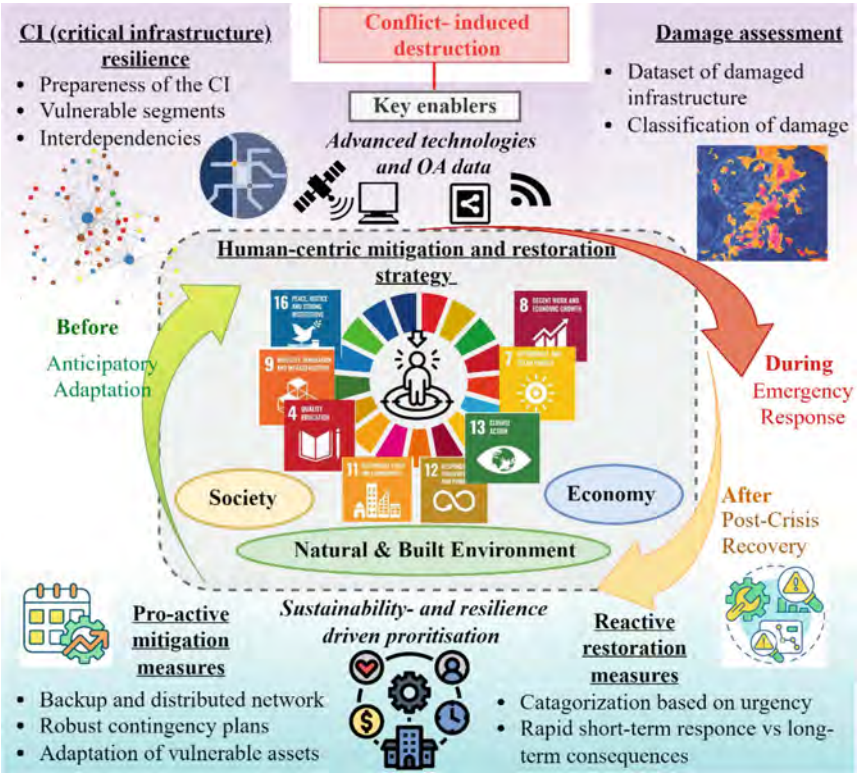


Fig. 1. The human-centric mitigation and restoration framework for war-torn cities.

Effective infrastructure restoration requires shifting away from merely restoring pre-disruption conditions. Traditional "engineering resilience"(R) [11], focusing on system's ability to return to a predefined equilibrium (R = 1), is insufficient for complex urban environments and post-war contexts. The demand for critical services is dynamic, evolving with demographic shifts, societal priorities, and geopolitical instability. Attempting to merely restore past conditions risks reinforcing outdated vulnerabilities [12, 13]. Although resilience models for natural hazards have advanced significantly, most remain insufficient for conflict contexts due to targeted infrastructure destruction, prolonged instability, and dynamic population displacement. Existing post-conflict approaches also tend to focus on social impacts while offering limited operational guidance for systems-level infrastructure recovery. Only a few works focus on conflict contexts [3, 6], and even these often restricted to specific infrastructural subsystems. This paper, therefore, provides a much-needed resilience framework for war-torn cities, evaluating affected critical infrastructure during ongoing conflict to support recovery planning and long-term peacebuilding efforts.

2.3 The Three Pillars of Reconstruction

The success of this framework relies on reconciling the competing demands of its three pillars:

A. Natural and Built Environment: Infrastructure as a System. Modern cities operate as complex, interconnected systems where infrastructure networks—transportation, energy, water, telecommunications—are deeply intertwined. Urban functionality arises from dynamic interdependencies, meaning the failure of one system can cascade across others, triggering systemic disruptions [14]. Traditional infrastructure resilience often focuses on hardening individual assets. However, in uncertain conflict environments, a more effective approach requires network-wide management to maintain overall system operability and essential flows, even when segments are degraded. Resilience, in this context, becomes a functional characteristic of the entire system to absorb, adapt, and recover functionality [15](see "CI resilience" and Natural & Built Environment pillar in Fig. 1).

While extensive research has modeled infrastructure interdependencies and guided recovery for natural hazards, these models are often insufficient for conflict contexts. They struggle to account for: targeted and prolonged damage, dynamic demand shifts due to population displacement, and fragmented governance. Existing frameworks integrating social, economic, and institutional factors also require recalibration for prolonged instability. Therefore, post-conflict recovery demands a holistic integration of network-level infrastructure performance, built structures, and dynamic supply-demand dynamics (Fig. 1, "Economy"), moving beyond asset-by-asset reconstruction toward systems-level restoration of interconnected urban lifelines.

B. Society: A People-Centric Approach and Capacity Building. Post-conflict urban recovery is fundamentally a multidimensional, people-centric process, not solely a technical one (see Society pillar in Fig. 1). Urban systems are socio-technical; infrastructure resilience is deeply linked to the social dynamics of communities. Traditional assessments often overlook that vulnerable groups face disproportionate risk, necessitating

equitable investments. Human needs evolve across recovery phases—from basic safety to livelihood and civic engagement—underscoring the need for dynamic, phase-specific strategies that view residents as "human sensors" providing real-time signals [8, 16]. Digital tools can amplify local voices and support situational awareness in conflict zones (Fig. 1).

Traditional models often underrepresent this interplay, which is exacerbated in conflict by abrupt population redistributions and uneven recovery trajectories, often decoupled from actual human needs (Society pillar in Fig. 1). Integrated paradigms like the Disaster City Digital Twin [17] support data integration and dynamic decision-making. Ultimately, sustainable recovery demands long-term capacity building and knowledge transfer, equipping local professionals with interdisciplinary tools. Success is measured not just by physical reconstruction, but by social inclusion, empowerment, and the long-term adaptive capacity of urban systems.

C. Policy, Governance, and Financial Innovation. Fragmented efforts and a lack of scalable solutions characterize post-disaster recovery. A multidisciplinary framework is essential to enhance coordination, optimize resources, and ensure long-term sustainability, aligned with global initiatives like the SDGs (see Fig. 1).

Beyond physical reconstruction, social infrastructure and community networks remain critical drivers of resilience. Strengthening social capital through inclusive participatory processes and fostering "bridging and linking" ties between diverse groups and authorities is crucial for equitable and sustainable recovery, especially in prevailing institutional fragmentation. Sustainable post-conflict recovery necessitates innovative financial mechanisms. Traditional aid models are often slow; thus, a shift towards pooled funding (e.g., Multi-Donor Trust Funds), novel financial instruments (e.g., Catastrophe Bonds for immediate capital, debt-for-resilience swaps for long-term investment), and Public-Private Partnerships (PPPs) is vital [18, 19] (Economy pillar in Fig. 1). International actors (e.g., World Bank, UNDP, IMF) remain instrumental in supporting financially resilient and socially inclusive recovery.

2.4 The Digital Enabler: Data-Driven Decision Making

Digital innovation acts as the transversal "enabler" (Fig. 1) that connects the three pillars. AI-driven damage assessment, digital twins, remote sensing, and network analysis support evidence-based planning in inaccessible conflict environments [13, 17], enabling more adaptive and resilient recovery [21]. AI/ML can assess damage from satellite, UAV, and sensor data, while digital twins can simulate recovery scenarios and optimise resource deployment. Remote sensing, GIS, and UAVs further support rapid mapping and damage assessment in inaccessible conflict zones [20]. The UADamage toolkit exemplifies this, combining multimodal sensing with AI to provide high-resolution, geolocated damage detection.

Beyond technical assessment, technology must bridge to civic participation. AI-enabled participatory planning leverages local knowledge and simulates scenarios using deep learning and knowledge graphs, though ethical safeguards against data bias and algorithmic opacity remain crucial in fragile post-conflict settings [21]. Digital platforms, such as Ukraine's Diia ecosystem, demonstrate how e-governance can evolve

from emergency service delivery to participatory urban planning. Social sensing, treating individuals as "human sensors" via social media, provides real-time situational awareness, community sentiment, and inclusive, bottom-up information flows complementing official channels. Network analysis identifies resilience gaps, prioritizing restoration based on system-wide impacts, while AI-assisted adaptive pathway frameworks enable flexible, adaptive decision-making under uncertainty.

For example, in a conflict-affected district where a hospital remains structurally intact, but access roads, power supply, and telecommunications are disrupted, the framework would not prioritise the hospital as an isolated asset. Instead, remote sensing and AI-assisted damage assessment could identify disrupted enabling infrastructure, while network analysis or digital twins could evaluate whether restoring a bridge, substation, or telecommunications node would generate the greatest system-wide recovery benefit. This dependency-aware logic enables reconstruction sequencing based not only on visible damage, but also on operational functionality and cascading interdependencies. Participatory platforms and local data could further support prioritisation by identifying population needs and accessibility constraints in real time. Such an approach illustrates how the framework can support adaptive and evidence-based reconstruction planning under highly uncertain post-conflict conditions.

However, the full potential of digital transformation is limited by the digital divide, lack of standardized frameworks, and the need for ethical AI. Transparency, interpretability, and investments in data-sharing, public-private partnerships, and capacity-building are critical to ensure equitable access and rebuilding public trust.

3 Conclusion

Post-war reconstruction requires a shift from fragmented rebuilding toward systems-based, multidisciplinary recovery. Our framework bridges the critical gap between existing restoration models—primarily developed for natural disasters—and the multifaceted, protracted challenges unique to conflict recovery. By recognizing the distinct nature of conflict-induced devastation and embracing an adaptive understanding of resilience, this framework moves beyond asset-centric rebuilding-a bottom-up approach- to sustained resilience of urban systems. It integrates three interdependent city domains—society, economy, and the natural & built environment - emphasizing people-centric strategies, innovative governance, and robust financial mechanisms. Implementing this vision requires overcoming siloed governance, conflicting agendas, limited local capacity, and rigid funding structures. In practice, this means that recovery decisions should prioritise not only visibly damaged assets, but also enabling systems — such as transport links, energy nodes, water systems, and digital connectivity — that unlock wider social, economic, and environmental recovery value. However, by embedding human agency, institutional learning, and cross-scalar coordination, this framework offers a scalable pathway to resilient, sustainable, and socially just urban recovery. Ultimately, success will be measured not only by physical reconstruction, but by the restoration of dignity, cohesion, and urban adaptive capacity.

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Use of Hygrothermal Simulation Software for Designing Sustainable Thermal Insulation Solutions

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Abstract. The hygrothermal behavior of building envelope components is a critical determinant of the sustainability of building constructions, extending design considerations beyond energy efficiency to encompass the physicochemical mechanisms that influence building pathology and service life. This paper investigates the role of dynamic hygrothermal simulation in the evaluation and comparative assessment of thermal insulation solutions under realistic operating conditions. For this purpose, simulations were performed using the IsZEB HygroThermal platform, supporting the informed selection of energy-efficient insulation materials. Through a case study on External Thermal Insulation Composite Systems (ETICS), the influence of moisture transport and thermal diffusivity on the in-service performance of insulation materials, namely mineral wool (MW), extruded polystyrene (XPS), and graphite-enhanced expanded polystyrene (EPS), is investigated, with particular emphasis on their role as "sacrificial" hygrothermal layers. Beyond energy performance, the study also examines functional and sustainability-related criteria, including fire behavior, vapor permeability, environmental impact, and long-term durability of ETICS solutions. The results demonstrate that simulation-based technical assessment, which accounts not only for laboratory-derived material properties but also for realistic boundary and operational conditions (steady versus unsteady), can support the rational design of building constructions that are not only energy-efficient but genuinely sustainable. In practice, dynamic hygrothermal simulation tools have become essential instruments for the research and development of insulation solutions for high-performance buildings that remain free from building-pathology-related defects.

Keywords: Thermal insulation · Hygrothermal simulation · Performance · Sustainability · Building pathology

1 Introduction

The selection of an appropriate thermal insulation material for a building application cannot be limited to merely meeting the thermal transmittance requirements defined by the applicable Greek Building Energy Performance Regulation (KENAK). Instead, it

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requires a more comprehensive approach that takes into account the actual performance and long-term sustainability of each solution. For example, if we consider External Thermal Insulation Composite Systems (ETICS) as a case study, it can be observed that the three insulation materials examined in the present study- graphite-expanded polystyrene (EPS, reference product: FIBRANeps 80 GRAFIT), extruded polystyrene (XPS, reference product: FIBRANxps ETICS GF), and mineral wool (MW, reference product: FIBRANgeo BP ETICS PLUS) - exhibit similar thermal conductivity values ($\lambda_D = 0.030–0.034$ W/m·K). Consequently, with minor variations in thickness (±1 cm), they can provide thermally equivalent insulation solutions. Nevertheless, their actual performance and long-term sustainability differ substantially.

In order to understand these differences, it is useful to first define the two fundamental concepts of "Performance" and "Sustainability." "Performance" relates to the actual operational cost of the building, as insulation materials exhibit different capacities to maintain their thermal properties over time, thereby affecting the real energy performance of the building in different ways [1]. "Sustainability," on the other hand, refers to the achievement of critical functional parameters in combination with the overall environmental performance and the expected service life of the system. It cannot be assumed that all insulation materials used in an ETICS provide the same level of fire protection, acoustic insulation, vapor permeability, seismic behavior, mechanical strength, environmental footprint, or durability [1].

The following sections present the factors influencing the performance and sustainability of insulation materials in ETICS, together with the results of dynamic hygrothermal simulations. These analyses highlight the role of scientific evaluation in the informed assessment of insulation materials. The aim of the present study is not to introduce a new numerical model, but to demonstrate how dynamic hygrothermal simulation can support the comparative assessment of ETICS insulation materials under realistic climatic and operational conditions.

2 Factors Affecting Performance

2.1 Moisture

The performance of thermal insulation materials after installation is directly influenced by the effects of moisture and temperature. The presence of moisture within the pores of insulation materials significantly affects their performance, as it increases thermal conductivity and reduces their ability to limit heat losses. A material that exhibits high insulating capacity under dry conditions may experience substantial performance degradation when saturated with water or water vapor [2].

Moisture can penetrate the insulation layer of an External Thermal Insulation Composite System (ETICS) through three main mechanisms: diffusion of water vapor from the atmosphere, capillary absorption of rainwater through the external rendering (particularly when cracks or aging are present), and condensation of water vapor within the cross-section when the local temperature falls below the dew point. The intensity and duration of these phenomena depend on several factors, including the chemical composition and microstructure of the material, the percentage and geometry of its pores, its hygroscopicity (ability to absorb moisture), its vapor permeability, and the condition of

the ETICS after aging. Consequently, evaluating the thermal performance of an ETICS cannot rely solely on laboratory measurements of thermal conductivity under dry conditions; instead, it must consider the actual operating conditions, where moisture content varies dynamically [2].

Indicatively, ETICS systems incorporating expanded polystyrene (EPS) may exhibit an increase in thermal conductivity of up to 11% under conditions of 70–75% relative humidity, while extruded polystyrene (XPS) shows a considerably smaller variation, around 6%, confirming its more stable hygrothermal behavior [3]. Furthermore, simulation experiments under conditions of intense rainfall have shown that prolonged exposure of EPS to artificial rain (120 mm/h) can increase water content by up to 2% by volume and raise the thermal conductivity coefficient from 0.0339 W/mK to 0.039 W/mK, corresponding to a reduction in actual insulation performance of approximately 15% [4]. Finally, hygrothermal analysis using the simplified Glaser method for the climate of Athens indicates a vapor diffusion mechanism leading to irreversible condensation at the dew point, with moisture accumulation of approximately 70 g/m^2 (about 8% of the weight of an EPS insulation layer) [2]. However, these results depend strongly on the building assembly and the assumed boundary conditions.

All of the above mechanisms may occur simultaneously, affecting each insulation material to a different extent. Among the insulation materials commonly used in ETICS, XPS, due to its closed-cell structure, exhibits lower water absorption [WL(T) 0.7%, total immersion] compared with EPS 80 [WL(T) 2%] (EN 12087), and therefore a smaller variation in thermal conductivity under real conditions is expected. Mineral wool, although it presents water absorption [WL(P) < 3 kg/m^2, partial immersion] (EN 12087), is an open-structure material with a vapor diffusion resistance factor $\mu = 1$ (EN 12086). This characteristic allows it to dry more easily, and therefore it is expected to demonstrate intermediate stability, between the more stable XPS and the less stable EPS [1]. As shown in the following sections, this behavior is confirmed through the use of advanced hygrothermal simulation software.

2.2 Thermal Diffusivity

A second mechanism influencing the actual performance of insulation materials, particularly during the summer months, is thermal diffusivity (α). Thermal diffusivity expresses the ability of a material to conduct heat relative to its capacity to store it. In essence, it is a measure of how quickly heat propagates through a material and is given by Eq. (1):

$$\alpha = \left[\lambda/(\rho \cdot cp)\right] \tag{1}$$

where λ is the thermal conductivity (W/m·K), ρ the density (kg/m^3), and c_p the specific heat capacity (J/kg·K) of the material [5].

The thermal diffusivity of mineral wool ($\alpha \approx 3.7 \times 10^{-7}$ m^2/s) is lower than that of XPS ($\alpha \approx 7.3 \times 10^{-7}$ m^2/s) and significantly lower than that of graphite-expanded polystyrene EPS 80 ($\alpha \approx 12.9 \times 10^{-7}$ m^2/s). Materials with high thermal diffusivity, such as graphite EPS 80, respond more rapidly to variations in external temperature, allowing heat to penetrate the building envelope more quickly. Conversely, materials with lower diffusivity, such as mineral wool, delay heat flow, providing improved thermal protection

during the summer period. This behavior is reflected in the phase shift, defined as the time delay (in hours) between the peak external temperature and the peak internal temperature during the summer period. The greater the phase shift, the more effective the thermal protection of the building envelope [6].

This effect can be qualitatively assessed through computational simulations. Using the German simulation software Ubakus [7], a typical dry construction wall assembly with ETICS, such as those increasingly used in modern hotel buildings in Southern Europe, was analyzed. The results show that even when different combinations of insulation materials exhibit the same thermal transmittance, they may still display significantly different dynamic thermal behavior. For example, a simulation of a dry construction wall incorporating mineral wool both in the internal insulation layer (d = 10 cm, ρ = 50 kg/m^3, λ_D = 0.034 W/mK) and in the ETICS layer (d = 10 cm, ρ = 90 kg/m^3, λ_D = 0.034 W/mK) showed that the thermal wave reached the interior approximately 1.5 h later - with corresponding benefits, depending on the building use profile, in terms of thermal comfort and reduced cooling loads - compared to a wall combining mineral wool (d = 10 cm, ρ = 15 kg/m^3, λ_D = 0.037 W/mK) with graphite EPS 80 (d = 10 cm, ρ = 16 kg/m^3, λ_D = 0.031 W/mK), despite the fact that both configurations exhibited the same thermal transmittance (U = 0.19 W/m^{2}K) [7].

3 Performance Simulation Scenario

The evaluation of building energy performance through the Greek TEE-KENAK software is based on steady-state computational models, which employ constant values of thermal conductivity (λ_D) and thermal resistance. These models do not account for the variation of thermophysical material properties over time or for real climatic conditions. In reality, however, the behavior of thermal insulation systems is dynamic, as it depends on fluctuations in temperature, humidity, and on phenomena such as vapor diffusion and condensation. These parameters interact within the cross-section of an External Thermal Insulation Composite System (ETICS), affecting thermal conductivity, service life, and the overall energy performance of the building envelope [8].

For a reliable assessment of the actual hygrothermal behavior of building components, dynamic simulation software is required, capable of solving the coupled processes of heat and moisture transfer both in space and in time. The advanced IsZEB HygroThermal software developed by the Centre for Research and Technology Hellas (CERTH) solves a system of coupled differential equations of temperature – moisture - heat storage (Eq. 2–4), which describe coupled heat and moisture transfer processes within the building component:

$$(\rho \cdot c + w \cdot 4187)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + S_h \tag{2}$$

$$\frac{\partial w}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial x}\left(D_w \frac{\partial w}{\partial \varphi}\frac{\partial \varphi}{\partial x}\right) + \frac{\partial}{\partial x}\left(\frac{\delta_0}{\mu}\frac{\partial(\varphi \cdot p_{sat})}{\partial x}\right) \tag{3}$$

$$S_h = h_{lv} \cdot \frac{\partial}{\partial x}\left(\frac{\delta_0}{\mu}\frac{\partial(\varphi \cdot p_{sat})}{\partial x}\right) \tag{4}$$

where T is temperature (K), w is absolute moisture content (kg/m^3), ρ is density (kg/m^3), c is specific heat capacity (J/kg·K), t is time (s), λ is thermal conductivity (W/m·K), h_{lv} is the latent heat of vaporization of water (J/kg), φ is relative humidity (−), D_n (Dw) is the moisture diffusion coefficient (m^2/s), p_{sat} is the saturation vapor pressure (Pa), δ_0 is the water vapor permeability in air (kg/m·s·Pa), μ is the vapor diffusion resistance factor (−), and x is the spatial coordinate across the thickness of the material (m).

The computational model implemented in the IsZEB HygroThermal platform has been validated for one-dimensional dynamic hygrothermal analyses according to EN 15026 and is based on established coupled heat and moisture transfer approaches used in hygrothermal simulation models. The platform also incorporates calculation approaches such as the Transfer Function Method (TFM) and the classical Glaser method for vapour diffusion analysis, while accounting for transient indoor and outdoor boundary conditions, including temperature and relative humidity variations [9].

The following section presents a performance simulation scenario using the IsZEB HygroThermal software for the comparative analysis of three typical insulation materials used in ETICS - graphite-expanded polystyrene EPS 80 (λ_D = 0.030 W/m·K), XPS (λ_D = 0.034 W/m·K), and mineral wool (MW) (λ_D = 0.034 W/m·K) - under realistic climatic conditions for Athens, using an insulation thickness of 10 cm, which exceeds the minimum requirements of National Regulation. The simulations were performed for representative ETICS wall assemblies under identical boundary conditions, with the insulation material being the only varying parameter. This approach allows the assessment of how hygrothermal properties beyond nominal thermal conductivity (λ_D) influence the overall energy performance of the building component.

The analysis was divided into two periods: a summer period (June–September) and a winter period (October–May), in order to evaluate the hygrothermal performance of each material in terms of simulated cooling and heating demand. During the summer period, the software simulated transient variations in temperature and humidity at the external envelope under identical boundary conditions for the examined ETICS wall assemblies. The results showed that the wall assembly incorporating mineral wool exhibited approximately 41% lower simulated cooling-energy demand compared with graphite EPS 80 and 16% lower demand compared with XPS. This superior performance is attributed to the low thermal diffusivity of mineral wool, which slows down heat transfer and increases the phase shift under high summer temperatures.

In contrast, during the winter period, the simulated energy balance changes. The results indicated that the wall assembly incorporating XPS exhibited the lowest simulated heating-energy demand, with 26.93 kWh/m^2, compared with 28.10 kWh/m^2 for mineral wool and 37.89 kWh/m^2 for EPS. The superior performance of XPS is attributed to its more stable hygrothermal behavior due to its low water absorption, which allows it to maintain nearly constant thermal conductivity under conditions of increased external humidity. Mineral wool, although characterized by excellent vapor permeability and drying capacity, shows slightly higher heat losses due to its open structure, while graphite EPS 80 demonstrates a more pronounced reduction in hygrothermal performance because of moisture accumulation and higher thermal diffusivity.

In terms of the overall simulated annual energy balance (heating plus cooling), XPS emerges as the optimal solution among the examined materials. Although mineral wool

performs better during the summer period, XPS provides the lowest simulated annual energy demand, while graphite EPS 80 - despite its lower nominal thermal conductivity (λ_D) - becomes the most energy-intensive solution because of its higher moisture absorption and thermal diffusivity [10, 11].

4 Factors Affecting Sustainability

4.1 Functional Factors

Energy performance, however important, is not sufficient on its own as a criterion for selecting an insulation material. The real sustainability of an External Thermal Insulation Composite System (ETICS) depends on how well the system responds to the functional requirements of the specific building and the environment in which it is located. A material with high thermal performance may prove unsuitable - or even unsafe - when specific conditions of use impose additional requirements, such as fire protection. For example, in buildings such as schools, hospitals, hotel facilities, or residential buildings located within forest areas, the requirement for high fire resistance becomes critical. In such cases, the use of ETICS incorporating mineral wool becomes not merely a design option but a necessity, since mineral wool provides high non-combustibility and is classified as A2-s1,d0 according to EN 13501-1. Furthermore, when the design criterion involves acoustic insulation, vapor permeability, and the natural drying capacity of the building element, mineral wool again becomes the most appropriate and practically the only viable choice. Owing to its fibrous and open structure, it exhibits a high sound absorption coefficient ($\alpha w \approx 0.95$) and excellent vapor permeability, with a water vapor diffusion resistance factor $\mu \approx 1$ for the examined material. Conversely, when the design priority concerns mechanical strength, resistance to flooding phenomena, or the reinforcement of masonry infill against seismic loads, the optimal choice becomes extruded polystyrene (XPS). With a characteristic tensile strength perpendicular to the surface of TR = 400–500 kPa, XPS provides excellent cohesion and can contribute to an increase in the strength of masonry infill by up to 40% under seismic loading conditions. At the same time, due to its closed-cell structure, it exhibits very low water absorption [WL(T) $\leq$ 0.7% according to EN 12087], ensuring high stability even in environments exposed to flooding events [12].

4.2 Environmental Performance

From an environmental perspective, the sustainability of insulation materials is assessed through Life Cycle Assessment (LCA), which evaluates the total energy and carbon footprint of a material from production to final disposal. Within this framework, mineral wool demonstrates a clear advantage, as it is the insulation material used in ETICS with the highest recycled content, reaching 50–90% recycled raw materials [13].

4.3 Aging and Service Life

The aging of insulation materials in External Thermal Insulation Composite Systems (ETICS) constitutes a critical factor affecting the long-term sustainability and service life

of the system. Unlike fibrous materials such as mineral wool, where dimensional change results solely from the thermal expansion of the solid mass, foam insulation materials exhibit two additional mechanisms of volume change: (a) expansion and contraction of the cellular structure due to variations in the internal pressure of the entrapped air or gas, and (b) moisture-related expansion, caused by the absorption and evaporation of water vapor within the pores. These mechanisms lead to more pronounced and faster dimensional changes in foam materials, an effect that becomes more intense as the density of the material decreases and thermal diffusivity increases. Consequently, in low-density EPS systems, the rate of expansion and contraction is significantly higher, resulting in greater stresses on the external rendering and an increased likelihood of microcracking or detachment during repeated thermal cycles. In contrast, mineral wool, due to its stable fibrous structure and very low thermal diffusivity, exhibits minimal and slow dimensional variation, contributing to long-term mechanical stability and reduced stress on the finishing layers [11]. Particular attention should also be given to graphite-enhanced EPS and XPS products, which exhibit a distinct anisotropy in heat transfer. Graphite, composed of layers of hexagonally arranged carbon atoms (graphene layers), conducts heat more efficiently within the planes of these layers (in-plane conductivity) and less efficiently perpendicular to them (out-of-plane conductivity). As a result, graphite-containing insulation boards can reach significantly higher surface temperatures, leading to increased thermal stresses in the external render, especially in buildings exposed to strong solar radiation in Southern European climates [14]. The superior stability of fibrous materials such as mineral wool is also supported by studies conducted by the Fraunhofer Institute, which indicate that ETICS systems based on mineral wool can achieve a service life of at least 60 years, nearly double that of systems based on EPS. This increased durability is largely attributed to the dimensional stability of mineral wool and the lower mechanical stress imposed on the external render layers [15].

5 Conclusions

The selection of the insulation material in the case study of External Thermal Insulation Composite Systems (ETICS) appears not to be a simple technical decision, but rather an architectural design choice with implications for performance, functionality, sustainability, and service life. The results of the hygrothermal simulations showed that, among the examined materials, mineral wool performs best under summer conditions, providing superior thermal comfort, while XPS performs better during winter conditions and in the overall annual energy balance due to its greater stability in the presence of moisture. From a functional perspective, mineral wool remains unmatched in terms of fire resistance, acoustic insulation, and vapor permeability, whereas XPS represents the safest solution for seismic reinforcement, flood-prone environments, and heavy façade claddings. From an environmental standpoint, mineral wool remains the most sustainable material, due to its high content of recycled raw materials and its potential for nearly complete recycling at the end of its life cycle. At the same time, the fibrous structure of mineral wool provides a particularly stable substrate for finishing layers, contributing to a service life approximately twice that of EPS-based systems. In contrast, graphite-based insulation materials appear particularly vulnerable under the climatic conditions

of Southern Europe. Therefore, the correct choice does not lie in identifying the "best" insulation material, but in selecting the right material for the right purpose. The architect, as the orchestrator of sustainability, must approach insulation not as a matter of thickness or numerical performance values, but as a strategic balance between climate, building use, and long-term durability. Modern hygrothermal simulation tools now provide the knowledge required to transform insulation from a simple construction layer into an active design instrument for the creation of sustainable buildings.

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Towards an Affordable and Sustainable Housing Sector in Cyprus: Integrating Prefabrication, Renewable Energy Systems, and Regulatory Reform

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Abstract. Housing affordability and energy poverty have emerged as interlinked challenges across Southern Europe and the Eastern Mediterranean, intensified by climate change, financialization of housing, and policy frameworks that prioritize capital inflows over social sustainability. In Cyprus, these pressures are compounded by rising land and construction costs, structural energy inefficiencies in the existing housing stock. While foreign investment has contributed to macroeconomic growth, it has also exacerbated housing access inequalities, particularly in coastal urban centers where local households face increasing displacement and energy vulnerability. This paper examines pathways toward establishing an affordable and sustainable housing sector in Cyprus through an integrated analysis of housing market dynamics, energy poverty, and construction innovation. Drawing on housing transaction data, affordability indicators, and energy statistics, the study documents the widening gap between housing demand and supply and the growing burden of combined housing and energy costs on middle- and low-income households. The paper argues that conventional affordability metrics underestimate this burden by failing to account for operational energy costs, particularly in a Mediterranean climate increasingly affected by heat stress. Building on this analysis, the research advances a multi-pronged framework that combines: (i) energy-efficient prefabricated construction as a cost-containment and sustainability strategy, (ii) the use of renewable energy systems and high efficiency heat pumps to reduce long-term household expenditure, and (iii) targeted regulatory reforms to recalibrate foreign investment toward socially productive outcomes. The paper concludes that aligning housing policy, energy transition strategies, and investment regulation is essential for transforming Cyprus's housing system from a speculative asset market into a socially resilient and environmentally sustainable sector.

Keywords: affordable housing · construction · energy · operation · cost · performance

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1 Introduction

Housing affordability has become one of the defining urban challenges of the early twenty-first century. Across Europe and the Mediterranean region, escalating housing costs, stagnant wages, and rising energy prices have converged to undermine access to adequate shelter, particularly for low- and middle-income households. These pressures are no longer confined to global cities or high-growth economies but increasingly affect small island states and secondary urban markets, where housing systems are highly sensitive to external shocks, capital inflows, and climate stressors.

Cyprus represents a critical case within this broader context. As a small, open economy with a liberalized real estate market, the island has experienced significant volatility in housing prices over the past two decades. Following the financial crisis of 2012–2013, the housing market rebounded rapidly, driven in part by foreign investment and state-supported residency-by-investment schemes. While these policies contributed to economic recovery, they also intensified structural inequalities in access to housing.

Housing affordability is conventionally assessed through ratios of housing costs to household income, with thresholds of 30–40% commonly used to identify cost overburden [1, 2]. However, in contexts such as Cyprus, where climatic conditions necessitate year-round cooling and increasingly frequent heat mitigation, these metrics are incomplete. Recent estimates suggest that approximately one-fifth of Cypriot households struggle to maintain thermal comfort in their homes, a condition exacerbated by poor building insulation, aging housing stock, and rising electricity prices [3, 4].

The interaction between housing affordability and energy poverty creates a compounding burden as shown in Fig. 1 below. Households priced out of newer, energy-efficient dwellings are often relegated to older buildings with higher operational costs, effectively transferring affordability pressures from upfront housing prices to long-term energy expenditure. Empirical evidence from Cyprus indicates that increases in property prices are closely correlated with rising rates of energy vulnerability, highlighting the need for integrated analytical/policy framework.

Against this backdrop, the pursuit of housing affordability in Cyprus cannot rely solely on demand-side interventions or market corrections. Structural changes in housing production and regulation are required. In recent years, prefabricated and off-site construction methods have gained attention as potential tools for delivering cost-effective, high-performance housing at scale [5]. By shifting construction from fragmented on-site processes to controlled factory environments, prefabrication offers opportunities to reduce costs, shorten construction timelines, and improve energy performance. When combined with renewable energy systems, high efficiency heat pumps and passive design strategies, prefabricated housing can significantly lower both embodied and operational energy demand, addressing affordability and sustainability simultaneously.

This paper argues that the convergence of housing affordability, energy poverty, and investment-driven market distortions in Cyprus demands a coordinated response that integrates technological innovation with regulatory reform. Rather than treating affordable housing, energy efficiency, and foreign investment as separate policy domains, the paper conceptualizes them as interdependent components of a single urban sustainability challenge.

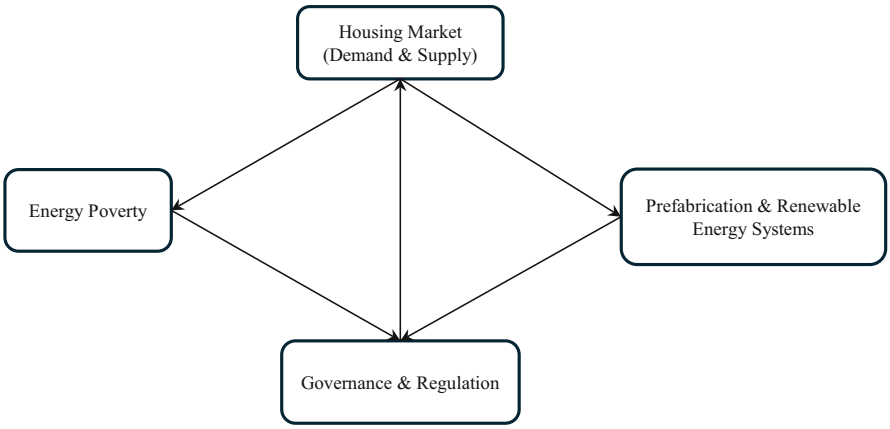


Fig. 1. Conceptual framework linking housing affordability, energy poverty, prefabrication, and governance in Cyprus.

2 Conceptual Framework: Housing Affordability, Energy Poverty, and Market Financialization

Housing affordability is a multidimensional concept that extends beyond the price of housing units to encompass broader socio-economic and environmental conditions. Traditional affordability metrics, such as the price-to-income ratio or housing cost overburden rates, have long been used to assess housing stress [1, 2]. While these indicators remain useful for comparative analysis, they are increasingly criticized for their limited capacity to capture the lived experience of housing insecurity, particularly in contexts characterized by volatile energy costs and climate stress.

In Mediterranean climates, housing affordability cannot be meaningfully assessed without accounting for energy consumption. Energy poverty, commonly defined as the inability of households to secure adequate energy services at affordable costs, has emerged as a critical dimension of social vulnerability [4]. In Cyprus, rising electricity prices, combined with an aging housing stock dominated by energy-inefficient construction, have intensified this vulnerability. As a result, households may appear marginally "affordable" under conventional metrics while facing severe operational cost burdens that undermine overall well-being. This paper adopts a combined housing and energy affordability framework, recognizing housing costs and energy expenditure as interdependent components of household vulnerability [6].

The literature on residency-by-investment programs highlights a recurring tension between short-term economic gains and long-term social costs [7]. In countries such as Portugal and Ireland, similar schemes contributed to rapid price escalation in urban centers, prompting policy reversals or program termination to protect housing access for residents. Cyprus's experience mirrors these dynamics though the impacts are intensified by the island's limited land availability and high concentration of development in coastal zones.

Bringing these strands together, this paper conceptualizes Cyprus's housing crisis as the outcome of three interacting forces: (i) affordability pressures driven by price-income divergence, (ii) energy poverty amplified by inefficient housing stock and climate conditions, and (iii) market distortions linked to financialized demand and investment-oriented regulation. Addressing any one of these dimensions in isolation is unlikely to yield durable solutions. Instead, an integrated approach is required, one that aligns housing production, energy efficiency, and regulatory frameworks within a sustainability-oriented policy agenda.

3 Housing Demand and Supply Dynamics in Cyprus

Foreign buyers have played a decisive role in reshaping demand patterns. According to transaction data reported by the Central Bank of Cyprus and national media sources, foreign nationals accounted for a substantial share of residential purchases between 2021 and 2024, particularly in Limassol, Paphos, and Larnaca.

This segmentation of demand has had two important consequences. First, it has shifted developer incentives away from lower-priced housing, reducing the supply of entry-level units suitable for local buyers. Second, it has contributed to upward price pressure across adjacent market segments, as mid-priced developments increasingly set benchmarks for land valuation and construction costs [8].

On the supply side, housing production in Cyprus has struggled to keep pace with demand growth, despite increased construction activity. Building permits and housing completions rose in the post-2018 period, reflecting renewed investor confidence and developer's response to foreign demand. However, the composition of supply is skewed toward higher-priced units, limiting the effectiveness of increased construction in alleviating affordability pressures. Several structural constraints exacerbate supply limitations. These include rising land prices in urban centers, increasing construction material costs, labor shortages in the building sector, and lengthy permitting processes [9].

The mismatch between supply growth and affordability needs is particularly evident in rental markets. As homeownership becomes increasingly unattainable for middle-income households, demand for rental housing has intensified, pushing rents upward and further increasing housing cost burdens. This trend is most pronounced in Limassol, where rental prices have surged in parallel with luxury and mid-market development aimed at foreign buyers.

The combined effect of demand-side pressure and supply-side rigidity has been a persistent imbalance in Cyprus's housing market. While aggregate supply has increased, it has not addressed the segments most relevant to local affordability. As a result, housing cost overburden rates remain relatively moderate at the national level but mask severe localized stress in coastal urban areas.

This imbalance is compounded by energy costs. Older housing stock, which disproportionately accommodates lower-income households, exhibits poor thermal performance and high energy consumption. As electricity prices have risen, households in these dwellings face escalating operational costs, effectively transforming housing affordability into a long-term expenditure challenge rather than a one-time purchase issue [10].

The demand–supply analysis thus reinforces the argument that Cyprus's housing crisis is not simply a matter of insufficient construction volume, but of misaligned production. Without targeted interventions to redirect supply toward affordable, energy-efficient housing, market-driven dynamics are likely to perpetuate exclusion and vulnerability.

4 Energy Poverty and the Housing – Energy Cost Nexus

The relationship between housing affordability and energy poverty constitutes a central but often underexplored dimension of urban sustainability [11]. In Cyprus, this nexus is particularly acute due to the Mediterranean climate, rising electricity prices, and the structural characteristics of the housing stock. While mild winters reduce heating demand relative to northern Europe, prolonged summers and increasing heatwaves have dramatically increased cooling needs, making thermal comfort a year-round concern.

Energy poverty in Cyprus is not evenly distributed. Households residing in older buildings, typically constructed before the introduction of regulations regarding the energy efficiency of buildings, face disproportionately high energy consumption. These dwellings are often occupied by lower-income households who have been displaced from newer housing by rising property prices. Consequently, affordability pressures manifest not only at the point of purchase or rental, but continuously through elevated energy bills.

Empirical evidence suggests a strong correlation between housing market dynamics and energy vulnerability. As electricity prices rose between 2021 and 2024, the combined burden of housing and energy costs exceeded 40% of disposable income for a substantial share of households in these areas [12]. This reinforces the argument that housing affordability assessments which exclude energy costs significantly underestimate real household vulnerability.

From a sustainability perspective, addressing energy poverty through retrofits alone is insufficient if households cannot access energy-efficient dwellings in the first place [13]. Structural solutions must therefore operate at the level of housing production, integrating energy performance into affordability strategies rather than treating it as an add-on.

5 Prefabrication and Renewable Energy Systems as Promising Solutions

Prefabricated construction offers a promising pathway for addressing both housing affordability and energy performance in Cyprus. By shifting production from fragmented on-site processes to controlled factory environments, prefabrication enables significant reductions in construction time, material waste, and labor costs. These efficiencies are particularly relevant in Cyprus, where rising material prices and labor shortages have increased the cost of conventional construction.

Evidence from Cypriot pilot projects demonstrates the affordability potential of prefabrication. The "*Prefab Eco-Smart House*" project shows that small-scale residential units constructed using a kit-of-parts approach can be delivered at substantially lower

cost per square meter than conventional housing, while achieving superior energy performance [6]. Beyond cost savings, prefabrication also offers scalability, allowing public or semi-public actors to deliver affordable housing at volume, an essential requirement for addressing structural shortages. Importantly, prefabrication aligns with sustainability objectives by reducing embodied carbon, minimizing construction waste, and enabling precision in insulation and airtightness. These characteristics position prefabrication not merely as a cost-cutting tool, but as a cornerstone of sustainable housing policy.

While reducing upfront construction costs is essential, long-term housing affordability depends equally on minimizing operational expenses. Renewable energy systems, such as solar thermal panels for domestic hot water production [14] or supply the heating system of the building [15], mainly in the mountainous area of the island, photovoltaics [16], biomass fired boilers, and the use of shallow geothermal or air-sourced heat pump technologies, autonomous or integrated/assisted with solar ones, are efficient and profitable solutions that can significantly minimize the overall cost of energy use [17].

Passive design strategies further enhance these benefits. Optimizing building orientation, shading, and thermal mass reduces cooling demand during summer months, while improved insulation mitigates winter heat loss. Together, these measures lower total lifecycle costs and enhance resilience to climate change.

From a policy perspective, the integration of solar systems into affordable housing should be treated as essential infrastructure rather than optional technology. Subsidies, feed-in tariffs, and low-interest financing can further enhance affordability, particularly when targeted toward low- and middle-income households.

6 Policy Framework for a Sustainable Affordable Housing Sector

The preceding analysis highlights the need for a comprehensive policy framework that aligns housing affordability, energy efficiency, and market regulation. Based on empirical findings and comparative international experience, this paper advances a multi-layered policy agenda.

First, regulatory recalibration of the investor citizenship scheme is essential. Mandatory contributions from foreign-targeted developments to affordable housing funds, combined with inclusionary zoning requirements, can ensure that investment inflows contribute directly to social sustainability. Transparency mechanisms, including public reporting on foreign acquisitions and housing stock utilization, are necessary to monitor impacts and adjust policy thresholds dynamically.

Second, targeted support for prefabricated affordable housing should be institutionalized. Public land allocation, fast-track permitting, and standardized building approvals can significantly reduce delivery times and costs. These measures would enable the state and local authorities to act as proactive housing providers rather than passive market regulators.

Third, the integration of high efficiency renewable energy systems assisted or not with heat pump technologies should be essential design priority. These systems not only drive the minimization of energy expenditures, but also accelerate the transition to a more affordable, sustainable and resilient building stock.

Fourth, integration of energy policy and housing policy must become a strategic priority. Retrofit subsidies and energy assistance programs should be directed toward households in energy-inefficient housing, while new affordable housing should be required to meet high energy performance standards from the outset.

Finally, financial instruments such as subsidized mortgages for first-time buyers, low-interest loans for energy-efficient (re)-construction, and vacancy taxes on underutilized properties can help rebalance demand toward socially productive uses of housing.

7 Discussion and Conclusions

The case of Cyprus illustrates the broader challenges facing small states and peripheral urban regions in an era of housing financialization and climate change. While foreign investment can stimulate economic activity, unregulated demand inflows risk undermining housing access, social cohesion, and long-term sustainability. The findings of this study demonstrate that affordability crises are not solely the result of insufficient supply, but of misaligned policy incentives that prioritize capital accumulation over social outcomes.

This paper has examined pathways toward an affordable and sustainable housing sector in Cyprus through an integrated analysis of housing market dynamics, energy poverty, construction innovation, and regulatory reform. The findings demonstrate that housing affordability challenges in Cyprus are driven by the interaction of demand distortions associated with foreign investment, supply constraints in affordable housing production, and rising energy costs linked to inefficient building stock. The contribution of this paper lies in advancing an integrated framework that positions housing affordability, energy poverty, and sustainability as inseparable policy challenges. While focused on Cyprus, the findings have broader relevance for other Mediterranean and small-state contexts confronting similar pressures. Future research should explore implementation pathways, governance models, and the long-term social impacts of affordable, energy-efficient housing on a scale.

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Energy and Performance: Net-Zero Energy, Carbon-Neutral Buildings, Renewable Energy Integration, and Smart Grids

Innovative and Sustainable Insulation Solutions for Zero-Emission Buildings

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Abstract. As climate change and environmental degradation intensify, the European Union's ambitious targets of reducing greenhouse gas emissions (GHG) and reaching climate neutrality by 2050 have become more urgent. Buildings account for approximately 40% of the total energy consumption and GHGs in the European Union. Additionally, throughout their construction, operation, use, renovation and demolition, buildings contribute to about 50% of extracted materials and over 35% of the EU's total waste generation.

The development of sustainable thermal insulation solutions which reduce energy consumption across the buildings' lifespan while embracing circular economy principles is essential to achieving a climate-neutral future and meeting Zero-Emission Building (ZEB) targets.

The objective of this paper is to present a methodology for the performance assessment of selected insulation solutions taking into account their energy and environmental characteristics. The assessment is carried out in a real case building located in central Europe, through virtual energy simulation. The main features evaluated for the selected building solution relate to the improvement of energy-efficiency performance, reduction of energy consumption, CO_2 emissions reduction as well as the potential improvement of the indoor comfort conditions.

Keywords: sustainable insulation solutions · construction sector · low-carbon building materials · Zero-Emission Buildings · circular economy

1 Introduction

The achievement of EU energy and climate goals demands a considerable reduction in overall energy consumption. More efficient energy use is a fundamental factor in the clean energy transition. Considering its importance, the EU has agreed to reduce the final energy consumption by 11.7% by 2030. Energy efficient solutions are applied across multiple sectors, including the building stock, transportation, and industry. In the construction sector, the use of high thermal energy performance building construction materials and the integration of smart technologies and appliances is of high priority [1].

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Since Europe aims to become the world's first climate-neutral continent by 2050, buildings play a crucial role in achieving this goal, as they are the largest energy consumers. Approximately 85% of buildings were constructed before 2000, of which 75% have low energy performance. Given that a large share of these buildings will still be in operation by 2050, the improvement of their energy efficiency is critical for the energy consumption reduction and the achievement of a fully decarbonised, net-zero-emission building stock. However, the annual rate of energy renovation remains very low, at 1% [2].

The building insulation market constitutes a rapidly growing sector, with a global value of €21.3 billion and an annual growth rate of 5.7%. In Europe, the market is estimated at €7.5 billion, with growth expected to increase to 6.3% per year. The majority of insulation is applied in walls (50%), followed by roofs (30%) and floors (20%). The residential buildings account for 57% of total insulation use, compared to 30% for commercial and 14% for industrial buildings [3].

The built environment is highly resource-intensive, accounting for approximately 50% of all extracted materials. This has an impact on multiple sectors, including the economy, local jobs, and quality of life. In the EU, the construction sector generates over 35% of total waste, while GHGs from material extraction, construction product manufacturing, and building construction and renovation are estimated to represent 5–12% of total national emissions. Enhanced material efficiency could reduce these emissions by up to 80% [4].

The development of sustainable thermal insulation solutions which reduces energy consumption across the buildings' lifespan while embracing circular economy principles is essential to achieving a climate-neutral future and meeting Zero-Emission Building (ZEB) targets.

The objective of this paper is to present a methodology for the performance assessment of selected insulation solutions taking into account their thermal and energy characteristics. The assessment is carried out in a real case building located in central Europe through virtual energy simulation. The main features evaluated for the selected building relate to the improvement of energy-efficiency performance, reduction of energy consumption, relevant CO_2 emission reduction and the potential improvement of the indoor comfort conditions.

2 Methodology

The paper presents a methodology for the performance assessment of selected insulation solutions taking into account their energy characteristics and their beneficial effects in the indoor environment.

The achievement of carbon neutral buildings requires the design of zero-emission buildings (ZEBs) and energy-efficient renovation strategies. Priority is given to the improvement of the building envelope so to reduce energy demand, before the integration of energy-efficient building technical systems or renewable energy technologies. In cases where transparent surface (glazing) is limited (i.e., low window-to-wall ratio), insulation measures have been proven particularly effective in the energy consumption reduction. As operational energy consumption decreases in new buildings, the embodied energy in building materials and components is of high importance [5].

A path to address the aforementioned EU objectives is supported by the SNUG project "Innovative methodology based in circular economy and artificial intelligence to foster the transition to Sustainable and very high eNergy performance bUildinGs at a cost optimal level". This EU-funded project proposes a methodology for the transition to Zero-Emission Buildings consisting of the following steps:

(i) Sustainable-by-design thermal insulation materials and prefabs
(ii) Digital Tool Assistant
(iii) Database of thermal insulation materials
(iv) Digital Building Logbook

The description of these main pillars is presented below.

2.1 Sustainable-By-Design Thermal Insulation Materials and Prefabs

The development of sustainable thermal insulation materials and lightweight prefabricated solutions is based on circular economy principles. Designed for integration in building envelopes, these solutions are suitable for both indoor and outdoor applications. The use of natural fibers, industrial by-products, and construction and demolition waste (CDW) improves thermal performance and energy efficiency while enhances sustainability in a cost-effective way.

Four main categories have been developed to address diverse insulation needs.

Aerated Eco-Concrete Blocks: Lightweight materials offering low density, improved thermal insulation, and material efficiency. They are produced using Ordinary Portland Cement blended with pre-treated biomass ash and recycled diatomite, as well as GGBFS-based geopolymers.

Sustainable Self-Leveling Mortars (SLMs): Consist of low-carbon-emission cement-based binders incorporating inorganic or organic phase-change materials (PCMs). They are designed for radiant floor systems where they can store and release heat when combined with smart control systems, optimizing energy use are improving energy efficiency.

Aerogel-Based Solutions: Provide exceptional thermal insulation and fire resistance while reducing energy demand. New solutions with lime-based renders and plasters (from CDW) and blow-in insulation (from thermal insulation waste) are being developed with lower embodied energy and cost. Aerogel's nanoporous, ultra-lightweight structure enables space-efficient insulation and reduce carbon emissions.

Biopanels: Bio-based panels made from renewable resources such as agro-waste, Posidonia, rice husk, and industrial hemp. They offer high thermal resistance, low carbon footprint, and contribute to the circular economy, as they require lower production energy requirements and biodegradability.

2.2 Digital Tool Assistant

An innovative Digital Tool Assistant (DTA) is developed to assist building professionals in the selection of the optimal combination of thermal insulation materials and planning

the installation for new construction and renovation projects, according to building's characteristics, type of project, end-user's requirements and available thermal insulation materials. The DTA is based on Artificial Intelligence (AI) and virtual simulation, providing building professionals with options for thermal insulation materials and building layouts, categorized according to sustainability, energy efficiency, safety and security and cost.

2.3 Database of Thermal Insulation Materials

An extensive database on thermal insulation materials is created, which includes technical information and life cycle assessment (LCA) data. Data such as embodied energy, thermal characteristics, fire resistance, and carbon footprint, among others is recorded. This database feeds into the DTA, leveraging and improving existing online databases on construction materials, cost calculations, real estate and LCA data.

2.4 Digital Building Logbook

A Digital Building Logbook (DBL) is created to collect and digitize all information - in a BIM-compatible format - ranging from materials and geometry to data on energy performance, insulation type applied, and the monitoring/analysis of the corresponding results.

3 Purpose of the Work

The purpose of the work is to assess the thermal and energy performance of a thermal insulation material and its potential contribution to the building internal conditions. The selected thermal insulation material serves as a key input to the DTA. This process constitutes the backbone of the overall methodology, supporting the decision-making process towards the Zero-Emission Buildings concept.

Within this context, an aerogel-based thermal insulation material is examined. Three scenarios are tested: i) a building without thermal protection on the external walls (Base Case), ii) a building insulated with the aerogel-based material (Scenario 1) and iii) a building with thermal insulation of polyurethane (PU) (Scenario 2). These scenarios are applied in a real-case building located in Central Europe.

3.1 General Description of the Building

The selected building is a single-family house located in Switzerland, situated in a semi-urban area and constructed in the 1960s. The building has a square floor plan, and its main entrance has southwest orientation with a deviation 44° from the north (Fig. 1).

The total floor area of the building is approximately 280m^2 and consists of three above-ground floors and one semi-basement.



Fig. 1. General view of the building [source Google Earth].

3.2 Building Envelope

The building's load-bearing structure consists of reinforced concrete without thermal insulation, while the walls are constructed using double-brick masonry without thermal protection. The total net area of the opaque external envelope (excluding openings) is 265.6 m^2.

The building is equipped with a pitched roof consisting of ceramic tiles with thermal insulation and the total surface area is 84.4 m^2.

All transparent elements consist of aluminum frames with thermal break, fitted with double-glazed units.

3.3 Building Technical Systems

The internal building spaces apart from the semi-basement are heated with the use of a heat pump with a seasonal Coefficient of Performance (SCOP) equal to 4.2. The terminal units of the heating system are radiators.

Artificial lighting is provided by ceiling-mounted luminaires equipped with LEDs. The total installed lighting power is approximately 285 W.

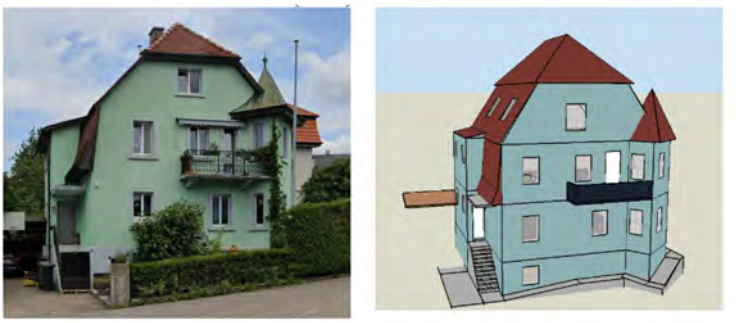
The Domestic Hot Water (DHW) is provided by thermal solar collectors installed on the roof with a total surface area of approximately 9.6 m^2.

3.4 Assessment Method

The assessment of the selected thermal insulation material was carried out with the use of the simulation tool, DesignBuilder v2025.1 [6]. This software is a virtual building modeling environment used for building performance analysis that integrates the EnergyPlus simulation engine. The assessment carried out takes into account the geometric, technical and operational characteristics of the building, providing – inter alia – detailed annual energy consumption data for all end-uses as well as indoor environmental data (Fig. 2a and b).

An aerogel-based thermal insulation material was considered, and the simulation was performed assuming it is installed as blow-in insulation within the external walls of the building. Aerogel is classified as a high-performance insulating material with a

significant capacity to improve the overall energy efficiency of the building [7]. For the purpose of this work, the thermal conductivity was specified as 0.014 $W \cdot m^{-1} \cdot K^{-1}$ [8]. This material is compared with a blow-in polyurethane insulation material of the same thickness (7 cm).



a. External view of the building. **b.** 3D view of the building model.

Fig. 2 **a.** External view of the building. **b.** 3D view of the building model.

4 Results

This section presents the outcomes of the energy performance assessment of the three scenarios (see Sect. 3). The results of the building simulation are given in monthly basis. The annual energy consumption, the CO_2 emissions, as well as the indoor environmental conditions (temperature and relative humidity) are presented below.

Figure 3 shows that the monthly energy consumption for space heating is the highest in the base case scenario, while the lowest is achieved with aerogel-based thermal insulation, resulting in a reduction of 288 kWh.

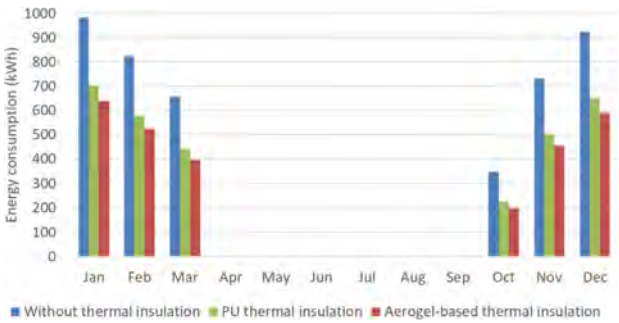


Fig. 3. Monthly energy consumption for space heating for the three scenarios.

Regarding annual energy consumption, it depends solely on the energy used for space heating, as all other uses remain unchanged across the three scenarios. Specifically, Scenario 1 and Scenario 2 contributes to an annual energy saving for space heating of 37.2% and 30.5% respectively. Additionally, the reduction in CO_2 emissions in Scenario 1 and Scenario 2 amounts to 163 $kgCO_2eq$ and 133.7 $kgCO_2eq$ respectively, corresponding to 9.1% and 7.5% relative to the base case [9].

Figure 4 indicates the monthly indoor temperature fluctuation for the base case and two scenarios along with the outdoor temperature, as well the relative humidity. The indoor temperature regimes have derived from free floating conditions. In January, the temperature difference between the insulation scenarios and the base case scenario is the highest, ranging from 4.57 °C to 3.86 °C, indicating the beneficial contribution of the thermal insulation in the energy performance of the building envelope. It is also noted that the indoor temperature in Scenario 1 is maintained at a higher level compared to Scenario 2, with an average difference of approx. 0.6 °C. During the heating period, the relative humidity in Scenarios 1 and 2 is considerably lower than the one of the base case scenarios. In December, the difference reaches 11.6% and 9.9% for Scenario 1 and Scenario 2, respectively, compared to the base case.

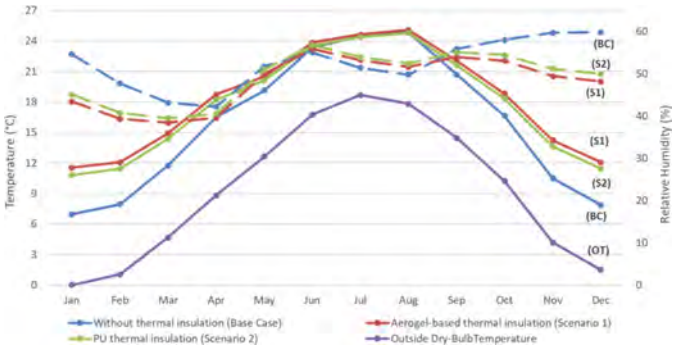


Fig. 4. Monthly indoor temperature & relative humidity fluctuation for the three scenarios.

5 Conclusions

This work presents the methodology developed within the SNUG EU-funded project, and supports the evidence-based decision making towards the transition to ZEB concept. The performance assessment of thermal insulation solutions was carried out, with the use of a building simulation tool, considering both energy and indoor environmental parameters.

The results demonstrate that the installation of the proposed aerogel-based thermal insulation solution substantially improves the energy performance of the building, resulting in 37.2% energy saving compared to the base case. Similarly, CO_2 emissions were reduced by 9.1%, confirming the environmental benefits of the thermal insulation material.

The installation of thermal insulation also contributes to the improvement of the indoor thermal conditions. Particularly, the proposed aerogel-based thermal insulation solution achieves the highest indoor temperatures under free-floating room conditions during the heating period, which is approximately 0.6 °C higher than PU thermal insulation. Moreover, both thermal insulation materials contribute to lower indoor relative humidity levels, further increasing indoor environmental quality.

Overall, the findings highlight the critical role of high energy efficient thermal insulation materials in the reduction of building energy consumption and CO_2 emissions.

Future work will focus on the development of more sustainable thermal insulation materials, integrating LCA data, so to support the advancement of the innovative DTA and DBL. This will serve as a useful tool for evaluating and selecting optimal thermal insulation materials, towards the ZEB concept and further support the EU climate targets.

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Next Generation Energy Performance Certificate Scheme of Buildings - Comfort Indicator

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Abstract. To date, the implementation of energy performance certificates (EPCs) varies significantly across EU Member States in terms of scope and available information, resulting in some cases in limited reliability, compliance, market penetration or acceptance by the users. Aspects like smart dimension or the interaction with the district energy system is only insufficiently covered in current EPC schemes. In order to become a catalyst for energy renovations, the next-generation EPC must provide an improved and more reliable service to the end-users. A next - generation energy performance certificate scheme has been developed in nine countries across Europe covering 40% of the EU building stock. This next – generation EPC scheme consists of ten innovative EPC features ranging from the smartness and comfort indicator to building logbooks and EPC databases. The paper presents in detail the "Comfort index". Although ensuring adequate levels of indoor air quality, thermal comfort, lighting and acoustics within buildings are among the most potent drivers for renovation, they are rarely covered by EPCs. Through the comfort indicator it is possible to assess the comfort levels in terms of the quality of the indoor environment for a specific building through reliable and evidence-based inputs. The work analyses all various parameters involved in the quantification of the index, and describes the methodology used.

Keywords: Energy performance · buildings · EPC · comfort index · assessment · certification

1 Introduction

Energy performance certificate (EPC) schemes have not evolved much since their first introduction in the Member States to meet the mandatory requirements of the Energy Performance of Buildings Directive (EPBD) [1]. Stakeholders have questioned their reliability but at the same time, they have been useful for the real estate industry. All Member States have legislation in place and existing infrastructure or systems to run EPC schemes. These schemes require evolution with the changing needs of the built environment and requirements to look beyond the energy consumption of buildings to take in elements such as better indoor comfort, reducing air pollution and others. Extending the

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functionalities of existing systems will create several pathways to update and manage next-generation EPCs [2]. Ten innovative EPC features have been identified ranging from the smartness and comfort indicator to building logbooks, financing options, and One stop shops. This work presents in detail the "Comfort index".

2 Innovative Energy Performance Certificate (EPC) Features

The innovative features for an EPC are illustrated in Fig. 1 [3]. The green coloured features focus on innovative handling of EPC data while the pink colored features explore new EPC indicators. The figure is encircled by four cross-cutting criteria: quality and reliability, user-friendliness, economic feasibility, and compliance with international standards. Each of the ten features is briefly described below.



Fig. 1. The ten innovative EPC features.

- Feature 1: Smart readiness - Smart technologies in buildings have the potential to contribute to increasing the energy efficiency of the building stock, to enhance the flexibility in smart energy grids, and to improve the comfort of building occupants. The introduction of a smart readiness indicator for buildings is included as a provision in the current Directive on the energy performance of buildings (EPBD) [4].
- Feature 2: Comfort - Although ensuring adequate levels of indoor air quality, thermal comfort, lighting and acoustics within buildings are among the most potent drivers for renovation, they are rarely covered by EPCs. This indicator would enable assessment of the levels of comfort in terms of indoor environmental quality for a specific building through reliable and evidence-based inputs.

- Feature 3: Outdoor air pollution. A significant contributor to air pollution is the building sector, which in many Member States still uses highly polluting fuels and technologies to cover heating, hot water and cooking needs.
- Feature 4: Real energy consumption - The gap between real energy performance and EPC modelled performance is a source of confusion to EPC users. The inclusion of real energy use data, increases trust in the EPC, enables automation of procedures and simplification of on-site inspections. The improved accuracy and better link with meter readings and billing information enhance user acceptance.
- Feature 5: District energy – the capacity of EPCs to assess and report on the potential for the building to benefit from – or contribute to – future development of district heating (and if relevant also district cooling) networks. It concerns the future decarbonisation of heat generation as well as the required transformation towards next-generation (smart, lower temperature) district heating systems.
- Feature 6: EPC databases – the value of EPC databases as a tool for quality assurance and data mining to enable more effective retrofit policies and programmes.
- Feature 7: Building logbooks - Logbooks have been recognised and developed in some countries to engage building owners and maximise the value of EPC data. The development of more dynamic logbooks could be supported by EPC registers and systems.
- Feature 8: Tailored recommendations - Cost and time constraints often result in EPCs containing generic, and not so useful, recommendations to the homeowner. Cost-effective approaches to deliver tailored renovation recommendations can enhance the instrument's impact on renovation activities.
- Feature 9: Financing options – Various sources of information on financial support can be provided alongside, and integrated in, EPC recommendations.
- Feature 10: One-Stop-Shops - OSSs are a key factor to reduce barriers and transaction costs for finding information regarding support schemes, craftspeople and public authorities. These functionalities of OSSs could also be linked to EPCs.

All these features can have an important impact on the use of EPCs.

3 Comfort Indicator

People spend approximately 90% of their time in buildings, so Indoor Environmental Quality (IEQ) has become an issue of increasing concern. This has become more relevant in the current pandemic where people are staying indoors even more. Occupant behaviour, awareness and level of acceptance of the indoor environmental conditions is essential for maintaining satisfactory IEQ. The indoor environmental quality (IEQ) includes four indicators: indoor air quality, thermal comfort, lighting, and acoustics [5]. A calculation methodology has been developed to quantify these four indicators and provide an integrated indicator for Comfort.

3.1 Thermal Comfort

According to ASHRAE 55 [6] and ISO 7730 [7] 'thermal comfort is that condition of mind which expresses satisfaction with the thermal environment'. The standards specify

the combination of indoor thermal environmental parameters (temperature, radiant temperature, humidity, air velocity) and personal parameters (metabolic rate and clothing insulation) for acceptable comfort conditions to occupants.

3.2 Indoor Air Quality

Indoor air quality refers to the air quality within buildings. Acceptable indoor air quality refers to air without harmful concentrations of known contaminants, with which the vast majority of exposed people are satisfied. It is directly related to the ventilation rates and concentration of indoor pollutants, which, in turn, are related to sick building syndrome (SBS), used to describe situations where occupants have acute health and comfort effects.

3.3 Visual Comfort

Visual comfort is defined in the European Standard EN 12665 as "a subjective condition of visual well-being induced by the visual environment" [8]. Visual discomfort can occur because of either too low or too high level of light. Visual comfort is a subjective measure dependent on certain factors such as illumination, luminance and brightness, luminous spectrum and risk of glare.

3.4 Acoustic Comfort

Acoustic comfort is achieved when there is no annoying noise in the environment. In office areas the acoustic quality is affected by the speech level of the occupants. Building elements play a significant role in offering external and internal sound insulation by acting as a barrier, absorbing or reflecting the sound waves [9].

3.5 Calculation of the Comfort Indicator

The methodology for the evaluation of the comfort indicator is based on evidence-based inputs. Operational rating uses measurements, surveys and checklists together, while asset rating uses only checklists. To identify the overall IEQ level, all four indicators as presented above were assessed independently based on multiple criteria. Under each criterion, certain parameters were met to achieve a required score. The score is awarded using the relevant assessment method (e.g. checklist, survey, monitoring etc.). Indicators, criteria and parameters were given relative weightings to calculate a total score and overall rating. The comfort rating gives an overall idea of the indoor environment and provides guidance in applying corrective measures [10]. Two procedures were developed to evaluate the comfort indicator, the Comfort Asset Rating Procedure (CARP) tool and the Comfort Operational Rating Procedure (CORP).

Comfort Operational Rating Procedure (CORP) Assessment
The operational rating is applicable to residential (single-family house, multi-family house, apartments) buildings, schools and offices and is complemented by the CORP assessment tool.

The comfort assessment of buildings is typically expressed as an operational rating when the building is occupied, and it is based on measurements, surveys and checklists under real status of occupancy. The method is used for occupied buildings used for more than a year. Operational rating records the actual comfort level of occupants over a course of a time period. Operational rating provides real information about how comfortable the buildings based on its use and operation.

The assessment approach for operational rating is based on:

- Measurements
- Surveys
- Checklists

To identify the overall IEQ level, all the indicators are assessed independently based on multiple criteria. Under each criterion, certain parameters must be assessed to achieve a required score (see Fig. 2).

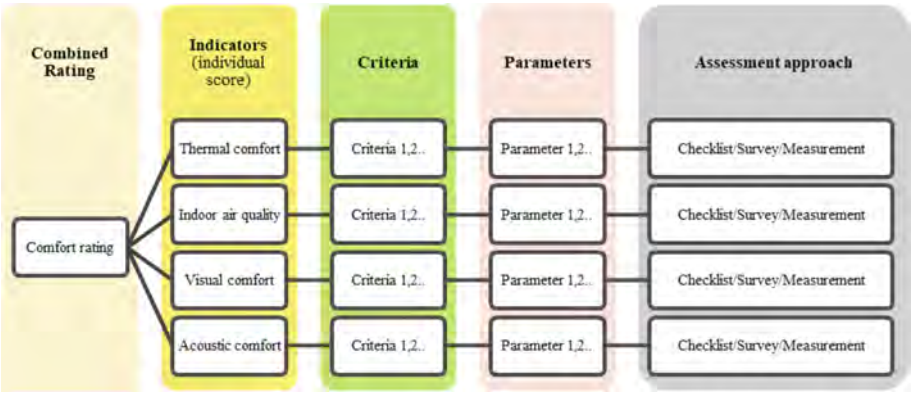


Fig. 2. Structure of criteria and parameters for each Comfort indicator.

The CORP Assessment Tool

The CORP assessment tool includes calculation tabs for each indicator (yellow box in Fig. 2) accompanying with the assessment approaches (grey box in Fig. 2) through criteria and parameters.

The criteria are the aspects that are assessed under each indicator. The list of criteria is prepared based on existing literature. The criteria are assigned to different or similar relative weightages based on expert inputs in the tool [11].

Certain parameters are used to assess each criterion based on the impact on comfort, health and well-being of the occupants. Relative weightage is assigned to each parameter based on expert input. Each parameter can obtain a score of 0 (worst) to 10 (best) which is assessed using a checklist. Individual scales for each parameter are developed for their scoring.

Figures 3 and 4 show the thermal comfort and the indoor air quality indicators of the CORP Assessment Tool respectively. Figures present the selected parameters, criteria, the scores, and the criteria weighting factors.

The comfort rating of the CORP Assessment Tool is displayed taking into account the weighted scores of the four contributing indicators (see Fig. 5).

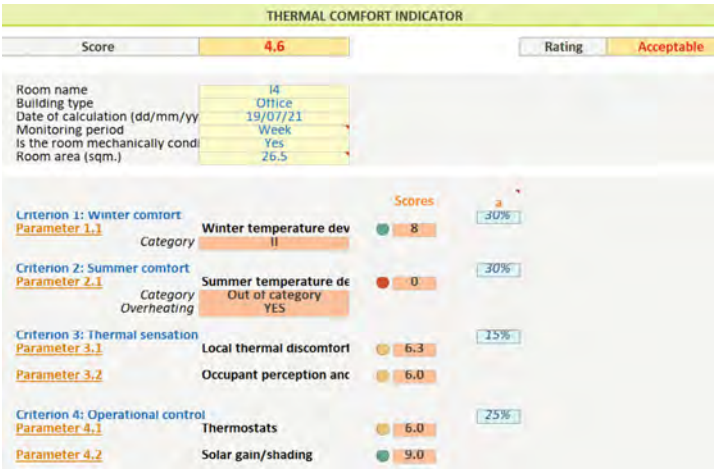


Fig. 3. Thermal comfort indicator of the CORP Assessment Tool.

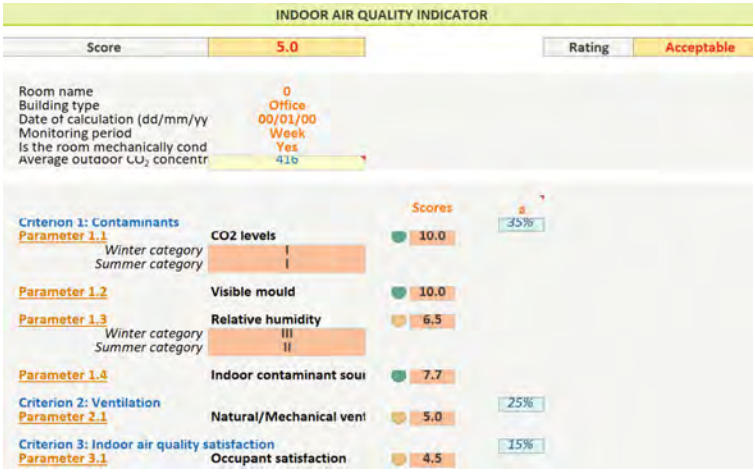


Fig. 4. Indoor air quality indicator of the CORP Assessment Tool.

Comfort Asset Rating Procedure (CARP) Assessment

The comfort asset rating procedure is meant for buildings that are newly constructed (not occupied yet), renovated (not occupied for more than a year) or existing that are not occupied. Its validity is limited until the buildings are occupied as the rating may not

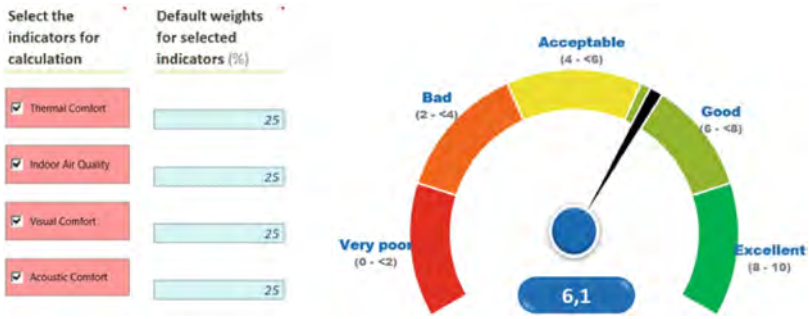


Fig. 5. Comfort rating output from the CORP Assessment Tool.

represent actual impacts of building use and operation accurately. It is recommended to get operational rating after a year of occupancy [12].

The same four indicators are assessed within the CARP: thermal comfort, indoor air quality, visual comfort, and acoustic comfort. To identify the overall IEQ level, all four indicators are assessed independently based on multiple criteria. Under each criterion, certain parameters must be assessed to achieve a required score (refer to Fig. 2 but omitting the last column "Assessment approach").

The CARP Assessment Tool

The CARP assessment tool includes calculation tabs for each indicator through criteria and parameters. The list of criteria is prepared based on existing literature. Criteria are assigned different or similar relative weightages based on expert inputs in the tool [12]. Figure 6 shows the visual comfort indicator of the CARP Assessment Tool. The comfort rating of the CARP Assessment Tool takes into account the weighted scores of the four contributing indicators and has the same layout as the CORP one (see Fig. 5).

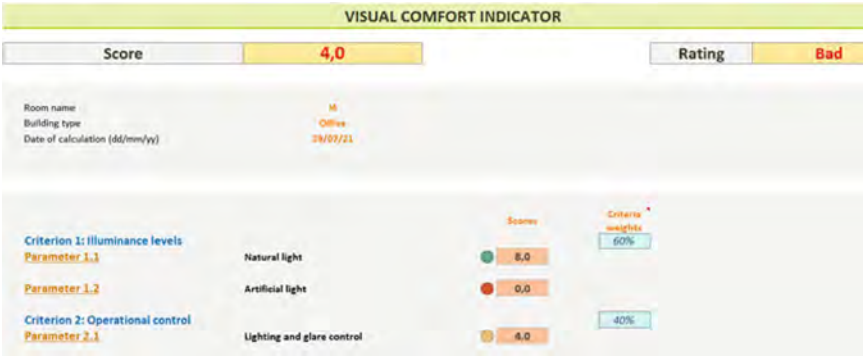


Fig. 6. Visual comfort indicator of the CARP Assessment Tool.

4 Conclusions

The "next-generation" EPC for buildings should include new features, aiming to improve compliance, usability and reliability. These features should be easily embedded in the EPC assessment processes and enabling the inclusion of new indicators on existing EPCs content in order to maximise their value for building owners and other end-users. One of these features has been presented in this work, the comfort indicator. The methodologies used to quantify its importance are simple, rather easy to assess, and they can be smoothly integrated in an existing EPC assessment.

The integration of a comfort indicator in EPCs allows the assessment of the IEQ and contributes to reducing negative health effects caused by inappropriate indoor conditions while improving the comfort and wellbeing of building occupants. The comfort indicator will enable a market push for better-performing buildings since it provides a rating which describes the quality of the indoor environment before and after an energy renovation process.

Thus, the ambitious European goals for achieving energy efficiency in buildings are supported while increasing the EPC comprehension and trust.

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Ensuring Thermal Comfort in nZEB Buildings: A Critical Analysis of Existing Approaches

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Abstract. Thermal comfort is an integral part of human well-being in the built environment. Impacts of prolonged periods of discomfort on mental and physical health are diverse, with possible severe health risks, especially on vulnerable sectors of population. Although its final assessment involves a subjective evaluation from the occupant, it is objectified under most methodologies and standards, becoming one of the main performance targets of energy efficient buildings, along with other indoor environmental quality parameters. While nZEB frameworks emphasize reducing overall energy consumption, this focus can sometimes lead to compromises in thermal comfort. To prevent these consequences, established thresholds, benchmarks and range limits of thermal comfort indicators are used in the design practice of newly built nZEBs or energy retrofits, in both the fields of architecture and building services. The purpose of the analysis is to provide a comprehensive and comparative review of existing approaches and possible shortcomings of thermal comfort in nZEBs. In the context of a changing climate, buildings must evolve in order to create favorable indoor environments throughout the year and to mitigate the impact of more frequent and severe weather events on the inhabitants. Possible shortcomings and overreliance on mechanical systems are further discussed and weighed against design choices, building envelope performance and occupant adaptative thermal comfort.

Keywords: thermal comfort · adaptive comfort · energy efficiency · nZEB · review · overheating

1 Introduction

Human well-being in buildings depends on indoor environmental quality (IEQ), which includes thermal comfort (TC), acoustics, air quality and lighting. The energy needed to maintain acceptable IEQ levels varies with building type, age, design, material choice and others. Among IEQ parameters, TC is one of the most complex, as it is associated with the highest energy use and the most significant health risks [1]. It is also the

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most extensively studied, although its health implications beyond comfort remain insufficiently explored [2]. Although TC is a subjective condition expressing satisfaction with the thermal environment [3], its assessment requires objective standards, since adaptation to temperatures outside comfort ranges may still involve health risks, especially for vulnerable population [4].

Projected temperature increases of 1.5–5 °C will further challenge TC and energy efficiency [5]. In response, European policies require high-performance standards for new and renovated buildings, including nearly zero-energy buildings (nZEB) and zero-emissions buildings (ZEB), with targets defined at national level. Within this framework, energy-efficiency measures should support and not compromise TC [6], particularly in terms of resilience, health and occupant safety, especially for vulnerable groups, in heating dominated countries [7]. This, in turn, requires strategies capable of maintaining acceptable indoor conditions while limiting resource use to the minimum necessary [8–10].

2 Methodology

The European Union (EU) climate and energy targets promotes a new building paradigm based on ZEB. As a transitional step, the Energy performance of Buildings Directive (EPBD) defines nZEB as a building with very high energy performance, supported to a significant extent by on site or nearby renewable energy, under typical operating conditions [6].

In terms of ASHRAE terminology, high-performance buildings extend beyond conventional energy-efficiency goals by also addressing environmental performance, economic value and indoor conditions that support occupant health, satisfaction and productivity [3].

The present study reviews the scientific literature on TC, with a focus on its relationship to high-performance buildings, particularly nZEB, while also considering Passive House (PH) and related frameworks. Rather than being exhaustive, the review synthesizes key findings and highlights the main gaps and challenges involved in maintaining TC while meeting energy reduction targets, with relevance to the Romanian context. Section 3 outlines the broader links between TC and high-performance buildings, while Sect. 4 examines this relationship more directly in terms of building performance.

3 Thermal Comfort in High-Performance Buildings

3.1 Thermal Comfort Assessment Methods

TC in a building can be assessed by several methods, the most widely used being Fanger's PMV–PPD model [3]. Based on the human body's heat balance, it considers four environmental parameters (air temperature, mean radiant temperature, relative air velocity and water vapor pressure), and two personal ones (clothing and activity) [11]. Although Fanger acknowledged climatic adaptation, he argued that preferred temperature show limited variation [12].

Within this framework, the PMV index expresses thermal sensation on a scale from −3 to +3 (see Table 1), while the PPD, derived from the PMV, estimates the proportion of dissatisfied occupants: even at PMV = 0, about 5% of people remain dissatisfied [12]. However, the model is less suitable for children, elderly or disabled people, and may misrepresent TC in naturally ventilated buildings [13].

Table 1. PMV scale ranging from −3 (cold) to +3 (hot)

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
−3	−2	−1	0	+1	+2	+3

The adaptive model, the second most widely used approach, relates acceptable indoor operative temperatures to outdoor climatic conditions and assumes that occupants can adjust their environment or behaviour to restore comfort. It is more particularly suited to naturally ventilated buildings and supports reduced energy use, by allowing wider temperature ranges [12]. However, both the adaptive and PMV models show limited accuracy in the prediction value of TC for small occupant groups [14]. Despite methodological differences, both are incorporated in European (EN ISO 16798) and the ASHRAE standards.

Other assessment methods include standardized interviews and questionnaires [2], as well as the use of fixed operative temperatures thresholds to define acceptable conditions. The latter approach assumes a fixed constant values for parameters such as relative humidity and air velocity [13], and does not account for occupant adaptation or subjective responses.

3.2 Thermal Comfort in High-Performance Buildings

The EPBD has progressively expanded its focus from energy efficiency to include comfort and IEQ [15]. In the EU, TC requirements for high-performance buildings are defined by EN 16798 and ISO 7730 with comparable criteria in ASHRAE 55. Building performance is primarily influenced by envelope design and quality, such as A/V ratio, continuous and efficient insulation, airtightness and controlled thermal bridging, along with orientation, solar gains and internal loads [16]. These factors must be addressed alongside passive strategies to ensure both energy efficiency and thermal comfort [6]. Local thermal discomfort is likewise influenced by parameters closely tied to building energy performance. Table 2 compares the main discomfort criteria set out in ISO 7730 and EN 16798 [17] with those included in the ASHRAE standard.

By reducing heat exchange with the outdoor environment, a well-insulated envelope improves thermal stability and promotes more uniform indoor air and surface temperatures, thereby supporting both energy performance and thermal comfort [21].

Adequate IEQ requires controlled humidity and air velocity, limited difference between air and radiant temperature, radiant temperature symmetry, vertical stratification below 2 °C, and temperature fluctuations below 0.8 °C [12]. These aspects of discomfort are closely related to envelope quality and building design. By reducing heat

Table 2. Local discomfort

ISO 7730, EN 16798	ASHRAE 55
Air draught	Ankle air speed and Draft
Vertical air temperature difference	Vertical air temperature difference
Floor	Floor surface temperature
Radiant asymmetry	Radiant temperature asymmetry
	Temperature variations in time

exchange with outdoor environment a well-insulated envelope improves thermal stability and promotes more uniform indoor air and surface temperatures, thereby supporting both energy performance and thermal comfort [18].

4 Challenges of Thermal Comfort in nZEBs

4.1 Key Challenges

Within the European context, nZEB buildings are among the most relevant categories of high-performance buildings. Their typically airtight envelopes improve energy performance but, in the absence of adequate ventilation, can increase the risk of summer overheating [15], as well as indoor pollutants accumulation and moisture-related problems such as mould. To mitigate these effects, mechanical ventilation systems are often required, although they may introduce additional costs and maintenance demands [9]. Given the strong influence of occupant behaviour on both IEQ and energy consumption [10], understanding building-occupant interaction throughout the year is essential reducing consumption without compromising TC.

4.2 Overheating Risk and Ventilations Challenges

Overheating has been widely reported across the EU [15], with increased vulnerability in Eastern European contexts [16, 19]. While efforts to reduce heating demand have promoted highly insulated and airtight buildings, rising Cooling Degree Days (CDD > 22 °C) [19] indicate an increasing risk of overheating. Several studies highlight that such dwellings are particularly susceptible to overheating due to high solar gains combined with elevated outdoor temperature, despite their compliance with EPBD and nZEB requirements [20]. Additional contributing factors include material properties, glazing configurations and surrounding urban context [21].

Empirical studies support these findings. Sameni et al. reported that 72% of monitored PH apartments failed overheating criteria [7], while Dartevelle et al. found that 18 out of 23 nZEB dwellings exceeded overheating limits, despite adequate winter comfort [9]. Although PH and nZEB standards differ, their comparison remain relevant given the influence of PH has on EPBD development [15]. Mlecnik et al. observed satisfactory winter conditions, but reduced summer comfort in PH dwellings, recommending measures to limit solar gains [8]. More stable indoor conditions were associated with lower

window to wall ratios and higher airtightness [9]. The importance of integrating climate change projections into nZEB design has been emphasized in the literature, particularly in relation to EPBD requirements and the risk of inadequate summer ventilation [8].

Night purge ventilation, although essential for TC, may pe constrained in dense urban areas [22], where tropical nights (temperatures averaging over 20 °C) have become increasingly frequent [23]. This is consistent with simulation-based evidence, showing that buildings compliant with current nZEB standards may still face increased overheating risk under future climate scenarios [24]. In this context, the EPBD promotes passive measures, such as shading and thermal mass [6], as primary strategies for limiting overheating. This is especially relevant in temperate climates, where active cooling and mechanical ventilation are not always mandatory in nZEB [12, 19]. Natural ventilation therefore remains a key residential strategy, although its effectiveness depends strongly on occupant behaviour.

Assessing overheating remains methodologically challenging. Fixed temperature thresholds are not suitable for all climates, while steady-state methods may overestimate cooling demands [5] and are poorly suited to unconditioned residential spaces. Adaptive methods also have limitations, particularly under very high outdoor temperatures (over 30 °C). For this reason, dedicated overheating assessment approaches, such as those proposed by CIBSE and PH, are widely used [15]. Maximum temperature is set by most relevant standards, ranging from 25 °C to 28 °C under various conditions, while a generalized conclusion by the WHO is that most sedentary people are safe in the range of 18 °C -24 °C [4]. Unlike general discomfort criteria, overheating assessment must account not only for peak temperatures, but also for the frequency, severity and duration of overheating events.

4.3 Occupant Behavior, Adaptive Thermal Comfort and Energy Use

Occupant behaviour plays a key role in both TC and energy use in nZEBs. Research highlights the subjective nature of TC and its direct impact on energy consumption, suggesting that integrating behavioural patterns into design and simulation can help reduce energy waste.

Adaptive comfort models are based on the premise that occupants thermally adapt through behavioral, physiological, and psychological mechanisms [25]. For instance, unoccupied dwellings are more prone to overheating [9, 26], while occupants can mitigate it through actions such as shading and natural ventilation [27]. At building scale, adaptive principles are reflected in bioclimatic architecture, rooted in vernacular responses to local climate conditions [28]. However, adaptation may also contribute to rebound effect, particularly in higher-income households, where increased comfort expectations can lead to higher energy use [10]. As shown by Barthelmes et al., the effectiveness of energy efficient buildings is strongly dependent on occupant behaviour, with user-driven factors such as setpoint preferences, appliance use and lighting significantly influencing overall consumption [29].

5 Discussion and Research Perspective

As noted Nunayon et al. [2], a key limitation in TC research is its frequent isolation from other IEQ factors. For instance, night or purge ventilation are essential for mitigating overheating, but in polluted, noisy or unsafe environments may prove inefficient. This can lead to increased reliance on mechanical and, consequently, higher energy consumption and potential rebound effects.

Integration of TC considerations into nZEB renovation strategies remains insufficiently explored, particularly in Eastern European contexts. In countries such as Romania, research on TC is still developing, despite increasing evidence of overheating risks not only in warmer regions but also in temperate and traditionally heating-dominated climates. Lessons from more advanced research contexts, such as the UK, could support the development of locally adapted approaches. At the same time, achieving nZEB performance in existing buildings presents both technical and financial challenges. Finally, the relationship between TC and socio-economic factors, such as energy poverty, requires further investigation. Ensuring adequate IEQ under low energy consumption conditions is essential for mitigating health risks and supporting occupant well-being.

Overall, the reviewed studies show that passive mitigation strategies can substantially reduce overheating risk in high-performance buildings, although direct quantitative comparison remains limited by differences in climate datasets, building typology, occupancy assumptions, comfort criteria and overheating indicators. The strongest recurring evidence supports the combined use of external shading, controlled natural/night ventilation and solar-gain management. Natural and night ventilation appear particularly effective, with some studies reporting reductions exceeding 70% in overheating hours, while external shading and lower-SHGC glazing improve summer comfort by limiting solar gains. Conversely, excessive airtightness, insufficient ventilation and prolonged warm periods or tropical nights are repeatedly associated with overheating, even in buildings compliant with PH or nZEB requirements.

6 Conclusions

Efforts to minimize heating demand in high-performance buildings may inadvertently compromise overall performance when summer conditions are insufficiently addressed. Without targeted passive measures, active cooling may become necessary even in temperate climates [22]. Although overheating risk remains manageable in many cases, climate change and urban heat exposure are likely to intensify this challenge, reinforcing the need for forward-looking design approaches consistent with EPBD objectives. Recent standards and methodologies increasingly define high-performance buildings not only in terms of energy use, but also through TC, health and wellbeing, while acknowledging the potential drawbacks of increased airtightness Accordingly, nZEB design should be approached holistically, with particular attention to envelope quality, thermal bridging, orientation, typology, window to wall rations and compactness. Inadequate design decisions may lead to localized discomfort, such as drafts or radiant asymmetry, as well as broader risks such as overheating.

Despite their limitations, adaptive comfort approaches appear particularly relevant for energy-efficient buildings, further underlining the central role of occupant behaviour

in maintaining acceptable indoor conditions. In the context of a changing climate, resilience to both summer and winter extremes becomes essential. Despite their limitations, adaptive comfort approaches appear particularly relevant for energy efficient buildings, further underlining the central role of occupant behaviour in maintaining acceptable indoor conditions.

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Framework Development for Assessing Positive Energy Districts

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Abstract. The assessment of Positive Energy District (PED) is a new, comprehensive methodology designed to bridge the gap between theoretical PED concepts and their successful, scalable implementation.

The primary goal of the assessment framework is to provide a standardized, objective framework for the planning, assessment, and evaluation of potential and existing Positive Energy Districts.

While it focuses on the development of the methodology which results from extensive consolidation exercises, merging expertise and concepts from several established initiatives, it ensures the assessment is holistic and robust. For this purpose, an analysis of 115 PEDs was used to distil 18 best practices for PEDs around strategic planning and visioning, governance and stakeholder engagement, financial and business models, technological integration and infrastructure, regulatory and policy frameworks, monitoring, evaluation and learning.

This provides the structure and scoring of PED assessment framework for successful replication of PEDs. The understanding of key success factors derived from actionable insights is a crucial output for improving a district's performance towards a sustainable future.

Keywords: Positive Energy District (PED) · Governance · Replication · Stakeholder Engagement · Standardization

1 Introduction

Positive Energy Districts (PED) are at the forefront of urban innovation, designed to address the pressing challenges of sustainable urban development. As cities around the world strive to reduce their carbon footprints and enhance energy efficiency, PED "laboratories" emerge as critical platforms for experimentation and validation of new technologies and solutions. PEDs are not just physical spaces but are conceptualized as dynamic environments where multidisciplinary approaches converge to create energy-positive urban districts. Introduced through the SET PLAN Action 3.2 [1], PED "Labs" serve as a "seeding ground for new ideas, solutions, and services," tailored to local

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needs and contexts. They take an integrative approach**,** considering technological, spatial, regulatory, financial, and social aspects. By bringing together researchers, city planners, businesses, and citizens, PED foster innovation, energy efficiency, and the shift toward climate-neutral cities.

1.1 Positive Energy Districts

The growing focus on sustainability and energy transition in the built environment has led to increased demand for the assessment of energy and environmental performance in buildings and urban areas. Assessment schemes for districts are designed specifically to evaluate the sustainability performance of urban districts. These schemes typically address aspects such as energy efficiency, environmental impact, social well-being, and economic viability [2].

PED's can be defined as "energy-efficient districts with net zero greenhouse gas emissions and an annual positive energy balance [3]. They prioritise the use of local renewable energy and resources. They seek to optimise the interaction and integration between buildings, the users, mobility, energy and ICT systems. PEDs strive to bring positive impacts to the wider energy system as well as social, economic, and environmental benefits to the communities. The assessment of the annual energy balance is open to any methods that are well defined and grounded on sound principles.

For the effective development, evaluation, and scaling of PEDs an evaluation framework is essential since it provides structured criteria for measuring the effectiveness and sustainability of these initiatives.

1.2 Key Performance Indicators

The PED Readiness Assessment (PED RA) methodology provides a concise, high-level approach to evaluate how prepared a district is to achieve net-positive energy performance. It is a strategic instrument designed to align diverse stakeholders and based on key performance indicators which describe the performance of a PED. As pointed out by Haase et al. (2026) it is a strategic instrument designed to align diverse stakeholders – from the public sector and city planners to industry leaders and technical developers – around the planning, deployment, and scaling of PED projects [4]. Establishing a common framework for assessment helps to manage the development of sustainable, energy-positive communities.

1.3 Objectives

The aim of this work was to analyse key performance characteristics of PED in the context of urban development and to categorise the multiple dimensions of their setting. The selection of the main assessed categories and key success factors have been based on a holistic and exhaustive survey of existing methodologies and highlights the multiple dimensions when talking about sustainability in districts.

2 Methodology

Starting point was the PED database with detailed descriptions of 115 PEDs and provides a wealth of information about new and refurbished PEDs and PED Labs [5]. The PED Lab Analysis (PLA) framework developed within the PED-EU-NET was used here to distil best practices and actionable insights from the 115 PEDs collected in the database [6]. It is based on a foundational framework to capture key PED characteristics and KPIs which served as the basis for consolidating definition and developing guidelines for their effective implementation. A case study examination was used to consolidate the framework. The analysis focused on how four core aspects (technological, social, financial, regulatory) interrelate with three key dimensions: stakeholders, life-cycle phase, and scale. This method was transferred to PEDs and the outcome is a list of best practices and actionable insights in a multi-dimensional setting.

3 Results

The best practices collected from the PED database showed that a multi-dimensional approach is needed for a successful replication of PEDs. They can be distinguished between strategic planning and visioning, governance and stakeholder engagement, financial and business models, technological integration and infrastructure, regulatory and policy frameworks, monitoring, evaluation and learning.

3.1 Strategic Planning and Visioning

Successful PED replication starts with a clear, ambitious, and adaptable strategic foundation (Table 1).

Table 1. Strategic Planning and Visioning

Best practice	Detail
1 Clear Vision & Ambitious, Holistic Goals	Go beyond merely achieving a positive energy balance. Define explicit, measurable goals that encompass environmental, social, and economic benefits. A holistic vision inspires broader stakeholder engagement and provides clear success metrics.
2 Contextual Analysis & Adaptability	Recognize that no two urban contexts are identical. Conduct a thorough pre-replication assessment of the specific local conditions. Existing Infrastructure: Grid capacity, district heating/cooling potential, transport networks.

(*continued*)

Table 1. (*continued*)

Best practice	Detail
3 Long-Term Commitment & Iterative Planning	PEDs are long-term projects spanning decades. Secure sustained commitment from all key stakeholders – political leadership, public administrations, private investors, and the local community. Acknowledge that the replication process will be iterative, requiring continuous learning, evaluation, and adaptation over time.

3.2 Governance and Stakeholder Engagement

Effective collaboration and inclusive processes are vital for navigating the complexities of PED development and replication (Table 2).

Table 2. Best practices of governance and sakeholder engagement

Best Practice	Detail
4 Inclusive Multi-Stakeholder Collaboration	Foster genuine partnerships among a diverse group of actors. This includes local authorities, citizens/ community groups, property owners, energy utilities, research institutions, technology providers, financial institutions, and local businesses. Early engagement ensures buy-in and leverages diverse expertise.
5 Early and Continuous Citizen Engagement & Co-creation	Involve residents and local businesses not just as beneficiaries, but as active participants in the planning, implementation, and operation phases. This builds trust, fosters a sense of ownership, ensures solutions meet local needs, and can lead to innovative co-created solutions. Address concerns proactively.
6 Adaptive and Agile Governance Models	Establish flexible governance structures that can adapt to unforeseen challenges and opportunities. PEDs involve multiple layers of decision-making, requiring coordination and alignment.

3.3 Financial and Business Models

Sustainable financing and attractive business models are fundamental for the economic viability and replicability of PEDs (Table 3).

Table 3. Best practices of financial and business models

Best practices	Detail
7 Diverse Funding Strategies & Blended Finance	Relying on a single funding source is risky. Combine public funding (with private investment. Explore blended finance mechanisms that combine different types of capital to de-risk investments.
8 Robust and Innovative Business Cases	Design clear and attractive business models for all participating entities. This includes defining revenue streams and cost structures.
9 Proactive Risk Mitigation & Management	Identify potential financial, technical, market, and regulatory risks early in the planning phase. Develop strategies to mitigate these risks.

3.4 Technological Integration and Infrastructure

Integrating smart technologies and robust energy infrastructure is at the centre of achieving PED status (Table 4).

Table 4. Best practices of technological integration and infrastructure

Best Practice	Detail
10 Integrated Energy System Design & Optimization	Move beyond isolated energy solutions to a holistic design that integrates renewable energy generation (solar PV, geothermal, wind where applicable), energy storage (batteries, thermal storage), efficient consumption, and smart grids (electricity, heating, cooling). Emphasize demand-side management and load shifting capabilities.
11 Smart Grid & Digitalization for PED Management	Implement advanced digital technologies for real-time monitoring, control, and optimization of energy flows within the district. This includes smart meters, building management systems (BMS), distributed energy resource management systems (DERMS), and data analytics platforms.
12 Maximizing Local Renewable Energy Production & Use	Prioritize the maximum feasible integration of local renewable energy sources. This includes not just rooftop solar PV, but also building-integrated PV, small-scale wind, geothermal, biomass, and waste heat recovery. Focus on maximizing self-consumption within the district.

3.5 Regulatory and Policy Frameworks

Supportive policies and streamlined regulations are essential for overcoming bureaucratic hurdles and incentivizing PED development (Table 5).

Table 5. Regulatory and policy frameworks

Best Practice	Detail
13 Supportive Local Policies & Urban Planning Integration	Local authorities play a crucial role by integrating PED principles into urban master plans, zoning regulations, and building codes. This includes mandating certain energy performance standards, requiring renewable energy installations, or setting aside space for energy infrastructure.
14 Navigating and Influencing EU & National Regulations	Understand the existing national and EU energy, building, and urban planning regulations. Identify how these frameworks can be leveraged to support PEDs (e.g., state aid rules, renewable energy directives). Proactively identify and advocate for changes to regulations that act as barriers.
15 Flexible and Streamlined Permitting Processes	Bureaucratic complexity and long permitting times can significantly hinder PED projects. Work with local authorities to simplify and accelerate approval processes for innovative energy technologies and integrated urban concepts.

3.6 Monitoring, Evaluation, and Learning

Continuous learning and knowledge sharing are vital for refining best practices and ensuring long-term success (Table 6).

Table 6. Best practices of monitoring, evaluation and learnings

Best Practice	Detail
16 Robust Monitoring Systems & Performance Validation	Implement comprehensive monitoring systems to track not only energy performance (generation, consumption, net balance) but also social, economic, and environmental indicators. This data is crucial for validating the PED status and demonstrating impact.
17 Continuous Learning & Adaptive Management	Treat each PED replication as a learning opportunity. Regularly evaluate performance against initial goals, identify deviations, understand root causes, and adapt strategies accordingly. This iterative process allows for constant improvement.

(*continued*)

Table 6. (*continued*)

Best Practice	Detail
18 Knowledge Transfer & Dissemination Strategies	Actively share insights, tools, and lessons learned from successful PEDs and their replication efforts with a wider audience. This includes publishing reports, organizing workshops (like yours!), creating online knowledge platforms, and developing practical guidelines.

4 Discussion

4.1 Actionable Insights for Strategic Planning and Visioning

(1) Develop a 'PED Vision Document' for each replication attempt that outlines these multi-faceted goals, ensuring alignment with broader urban development and climate strategies. (2) Develop a 'Replication Suitability Matrix' that helps assess the transferability of best practices from source PEDs to target replication sites, allowing for tailored adaptations rather than direct copying. (3) Establish a 'PED Replication Steering Committee' with representatives from critical stakeholders committed to long-term oversight and support. (4) Implement 'learning loops' within the replication plan, scheduling regular reviews and opportunities for adjustment.

4.2 Actionable Insights for Governance and Stakeholder Engagement

(1) Design a 'Collaborative PED Platform' or 'Governance Forum' from the outset, clearly defining roles, communication channels, and decision-making processes for all partners. (2) Consider using Memoranda of Understanding (MoUs) to formalize commitments. (3) Implement diverse 'Citizen Engagement Toolkits' (e.g., workshops, participatory design charrettes, online feedback platforms, energy literacy programs) tailored to different demographics and stages of the project. (4) Implement a 'Multi-Level Governance Framework' that clarifies responsibilities and communication flows across different administrative tiers. (5) Consider 'Living Lab" approaches where rules and technologies can be tested and adapted in a real-world setting.

4.3 Actionable Insights for Financial and Business Models

(1) Develop a 'PED Financial Portfolio' that maps out potential funding sources for each phase of replication (planning, investment, operation) and identifies suitable blending strategies. (2) Explore 'Energy-as-a-Service' or 'Building-as-a-Service' models. (3) Conduct 'Cost-Benefit-Analysis (CBA)' and 'Total Cost of Ownership (TCO)' assessments for the entire lifecycle of the PED, demonstrating long-term value for all stakeholders, not just initial investment costs. (4) Implement a 'PED Risk Register' that systematically identifies, assesses, and tracks risks, along with clear mitigation plans. Share learnings from previous PED projects on risk management.

4.4 Actionable Insights for Technological Integration and Infrastructure

(1) Utilize 'Energy System Modelling & Simulation Tools' during the design phase to optimize the interaction between different energy components and predict performance under various scenarios. (2) Prioritize 'Open Data Protocols and Interoperability Standards' (e.g., OpenADR, CIM, digital twins) to ensure seamless communication between various devices and systems, preventing vendor lock-in and enabling future upgrades. (3) Conduct a comprehensive 'Local Renewable Energy Potential Assessment' for the replication site. Explore 'Energy Community'models to facilitate local ownership and direct consumption of renewable energy.

4.5 Actionable Insights for Regulatory and Policy Frameworks

(1) Develop a 'PED Enabling Policy Toolkit' at the municipal level, identifying relevant ordinances and planning instruments that can facilitate PED development and expedite permitting processes. (2) Establish a 'Regulatory Watch Group' within your PED replication initiative to monitor policy developments and prepare informed feedback for legislative processes. (3) Develop 'Fast-Track Permitting Guidelines' for PED-related components (e.g., district heating loops, large-scale PV installations, battery storage) or establish a dedicated 'PED Project Office' within the municipality to guide projects through the approval process.

4.6 Actionable Insights for Monitoring, Evaluation and Learnings

1. Develop a 'PED Monitoring Protocol' with standardized KPIs aligned with EU-level definitions. Utilize digital platforms and sensors for automated data collection and analysis. (2) Establish 'Learning Labs" or "Peer-to-Peer Exchange Forums' where replication projects can openly share challenges and solutions, fostering a culture of continuous improvement. (3) Contribute to or establish an 'Open PED Knowledge Hub' (e.g., integrating with existing EU databases) to make data, best practices, and tools easily accessible for future replication efforts. (4) Develop 'Replication Playbooks' or 'How-to Guides' based on proven strategies.

5 Conclusions

The analysis of 115 PEDs was useful to distil 18 key success factors for PEDs around strategic planning and visioning, governance and stakeholder engagement, financial and business models, technological integration and infrastructure, regulatory and policy frameworks, monitoring, evaluation and learning. The PED assessment framework must provide the structure and scoring for successful replication of PEDs. The understanding of key success factors is a crucial output for improving a district's performance towards a sustainable future.

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Centralized Short-Term Thermal Energy Storage in Hybrid Heat Pump Building Systems

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Abstract. The impact of short-term thermal energy storage (TES) on heat pump–based systems in newly constructed multi-apartment buildings is evaluated for two emission concepts: a medium-temperature fan-coil system and a low-temperature radiant (floor/wall/ceiling) system. An optimized TES volume of 2.0 L/m^2, derived from parametric analysis, was applied to domestic hot water (DHW) and space heating. System-level considerations indicate that extending TES to cooling would provide only limited additional energy benefits while increasing investment and control complexity. TES integration achieves annual electricity savings of 10–14%, primarily through improved effective seasonal heat pump performance and winter peak load mitigation, with the largest gains observed for DHW operation. Although space cooling represents a small share of annual electricity demand, it governs installed system capacity, whereas TES reduces required heating capacity by smoothing coincident DHW and space-heating peaks. Low-temperature radiant systems achieve lower absolute electricity consumption, while TES provides comparable relative benefits across both emission technologies. Rooftop photovoltaic integration is proposed as a future upgrade toward a hybrid renewable configuration.

Keywords: Air-to-water heat pumps · Short-term thermal energy storage · Domestic hot water · Peak load reduction · Energy savings

1 Introduction

In the 21st century, energy challenges have become critical, with buildings playing a central role in reducing energy consumption and CO_2 emissions. Heating and cooling account for more than 50% of global final energy use and approximately 40% of CO_2 emissions, with space conditioning representing up to 80% of building energy demand in colder and hotter climates [1, 2]. Within Europe, heating and cooling in buildings comprise about half of total energy demand, over 60% of which is still supplied by fossil fuels [3]. When domestic hot water (DHW) is included, these end uses account for nearly 80% of direct CO_2 emissions from buildings [3], highlighting the need for improved heating technologies and further energy efficiency measures. While space-heating demand can

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be decreased through enhanced envelope performance and reduced system operating temperatures, DHW consumption remains relatively constant. Consequently, its share of total building energy demand increases and is expected to grow further as building energy efficiency improves [4, 5].

In Serbia, households are the largest final energy consumers, accounting for approximately 40% of total final energy consumption. Space heating accounts for roughly 66%, and DHW preparation contributing around 12% [6, 7]. About 75% of households rely on individual heating systems, mainly using firewood, electricity, and natural gas, while the rest are connected to district heating networks. Although district heating is widespread in around 50 of the biggest cities and included in new multi-family buildings, household connections are growing slowly at about 0.4% per year [7], and many new buildings avoid it due to high costs, limited flexibility, and reliance on a single provider. As a result, heat pump (HP) based systems are starting to emerge, offering space heating, DHW, and cooling with greater energy efficiency, lower long-term costs, fewer emissions, and more independence.

In recent years, the dominant residential typology in Belgrade—and in a few other major Serbian cities—has been the mixed-use mid-rise building, typically realized as a single-core linear slab block with 6–10 above-ground storeys, ground-floor comercial spaces, underground parking, and a total heated floor area of approximately 1,200–2,500 m^2. These buildings are generally designed in accordance with the Serbian Rulebook on Energy Efficiency of Buildings [8] to achieve an annual heating energy demand of up to 60 kWh/m^2. Buildings with lower energy demands are less common and are typically found in higher-cost projects or in more desirable urban locations.

2 System Description and Calculation Method

In energy-efficient residential buildings with modest specific space-heating demand, the structure of final energy consumption changes significantly, and the share of energy used for DHW becomes proportionally larger than in conventional buildings. Under these conditions, thermal energy storage (TES) becomes increasingly important, particularly when HPs are used as the primary heat supply system. TES enables the decoupling of heat generation from heat demand, reducing compressor cycling, improving the seasonal coefficient of performance (SCOP), and allowing heat pumps to operate in more favorable thermodynamic regimes, such as lower supply temperatures and longer continuous operating periods.

The role of TES is even more pronounced when heat pumps provide both space heating and DHW, as DHW production requires higher temperatures and is characterized by short-term peak loads that do not coincide with average heating demand. TES tanks allow DHW to be produced outside peak demand periods—such as during off-peak electricity tariffs or times of higher renewable electricity availability—while hot water delivery is supplied from storage. This approach avoids oversizing the heat pump for DHW peak power, reduces installed capacity, improves overall energy and economic performance, and enhances operational flexibility, load management, and integration with renewable energy sources and smart grids.

In line with the above considerations, the analytical part of this study examines the optimal sizing of TES for a representative new residential building in Belgrade, taking

into account local climatic conditions and the structure of space-heating and DHW demand. A representative air-to-water heat pump system (Fig. 1) with radiant or fan-coil heat-emission systems is analyzed to quantify energy savings and evaluate the TES volume range that yields the greatest overall performance benefits.

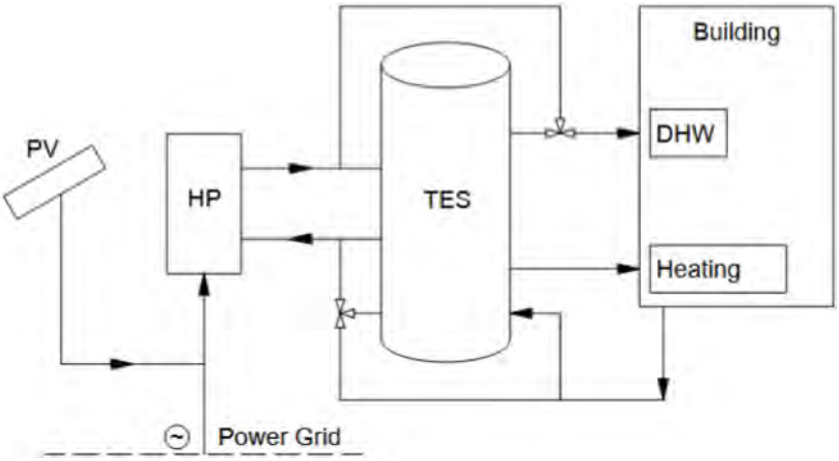


Fig. 1. TES connection scheme for DHW and heating mode.

Reliable estimation of DHW energy consumption in residential buildings remains challenging due to limited data availability and strong dependence on occupancy patterns, dwelling characteristics, user behavior, distribution losses, and the presence of non-residential functions. Based on a comprehensive synthesis conducted for the Budapest metropolitan region [5]—which is socio-technically comparable to urban areas in Serbia—an average DHW energy demand of 28.2 kWh/m^2·year is adopted in this study. A simplified seasonal DHW demand profile was assumed, with monthly demand during the summer period (June–August) taken as 20% lower than during the rest of the year due to higher cold-water inlet temperatures, the consequently reduced energy required for water heating, and reduced occupant presence during summer, resulting in monthly values of 1.98 and 2.47 kWh/m^2, respectively, while preserving the annual average demand.

Climate-based seasonal energy demand were derived from the multi-city dataset presented in Table 1 and used to disaggregate the annual specific energy demands for space heating, space cooling, and domestic hot water preparation into monthly values for Belgrade (Fig. 2). The dataset was compiled from multiple sources [9–14] and includes average January and July air temperatures, heating design temperature, heating and cooling degree days, average wind speed and relative humidity, day–night temperature differences in January and July, as well as 10-year averages of annual global insolation and average daily insolation in December and July for the selected cities. An annual specific space heating energy demand of 60 kWh/m^2 was distributed over the heating season (October–April) using monthly shares proportional to the heating degree days for Belgrade, with peak demand occurring in December and January.

The annual specific cooling energy demand was estimated by scaling the heating demand using the ratio of cooling to heating degree days for Belgrade and applying an empirical correction factor to account for typical solar and internal heat gains in residential buildings [15], resulting in an estimated cooling demand of approximately 18 kWh/m^2·year. This cooling demand was distributed over the cooling season (May–September) based on mean monthly outdoor temperatures for Belgrade, with peak demand occurring in July and August.

Table 1. Climate data for selected cities in Serbia and the region.

	Belgrade	Novi Sad	Niš	Prišti-na	Subotica	Vra-nje	Thess aloniki	Buda-pest
$T_{AV,\,Jan.}$ [°C]	0.8	0.8	−0.5	−0.6	0.5	−1.0	4.2	−0.5
$T_{AV,\,July}$ [°C]	24.3	23.7	23.4	21.5	23.3	26.4	27.4	22.1
$T_{Des.H.}$ [°C]	−12.1	−14.8	−14.5	−19.8	−14.8	−15.3	−6.0	−13.0
HDD_{18} [K day]	2550	2650	2450	2570	2750	2500	1850	2800
CDD_{22} [K day]	520	480	620	560	430	670	950	650
$w_{AV,\,Jan.}$ [km/h]	11.2	11.1	8.1	8.0	12.5	8.1	8.8	10.7
$w_{AV,\,July}$ [km/h]	8.6	8.7	9.0	8.5	12.4	11.7	8.2	10.3
$RH_{AV,\,Jan.}$ [%]	83	87	–	84	–	–	75	84
$RH_{AV,\,July}$ [%]	50	49	–	57	–	–	45	58
$\Delta T_{DN,\,AV,\,Jan.}$ [K]	4.0	4.4	5.0	5.0	4.5	6.5	5.0	5.5
$\Delta T_{DN,\,AV,\,July}$ [K]	11.0	11.0	13.5	13.0	11.0	14.5	11.0	12.5
$H_{y,AV10}$ [kWh/m^2]	1440	1390	1520	1570	1380	1540	1820	1410
$H_{d,AV,\,Dec.}$ [kWh/m^2]	1.2	1.1	1.4	1.5	1.1	1.4	1.7	1.1
$H_{d,AV,\,July}$ [kWh/m^2]	6.6	6.3	6.7	6.9	6.2	6.6	7.4	6.4

For a model residential building with a heated floor area of 2,000 m^2, air-to-water heat pumps without TES were sized to meet peak thermal loads based on representative specific design heat load values (W/m^2) for the Belgrade climate. This resulted in required capacities of approximately 145 kW for combined DHW production and space heating and 90 kW for space cooling with fan-coil systems, while low-temperature radiant systems required about 115 kW and 50 kW, respectively.

The introduction of TES for DHW and space heating significantly reduces peak heating capacity. A parametric Python-based analysis was performed for both fan-coil and radiant heating systems by varying the TES volume and evaluating the resulting peak load reduction and annual electricity consumption under identical boundary conditions. The analysis assumed climate-based seasonal demand profiles for space heating and DHW, while maintaining fixed annual heating and DHW energy demands (i.e., constant annual energy balances independent of TES configuration). The results indicate that the optimal TES volume lies within the range of 1.6–2.1 L/m^2. Beyond this range, only marginal reductions in annual electricity consumption were achieved, while storage costs and space requirements continued to increase.

For subsequent calculations, a representative value of 2.0 L/m^2 is adopted within the identified optimal range. Accordingly, the required installed heat pump capacity for DHW preparation and space heating is reduced to approximately 100 kW for fan-coil systems and 80 kW for radiant systems, whereas the required cooling capacity remains unchanged compared to systems without TES.

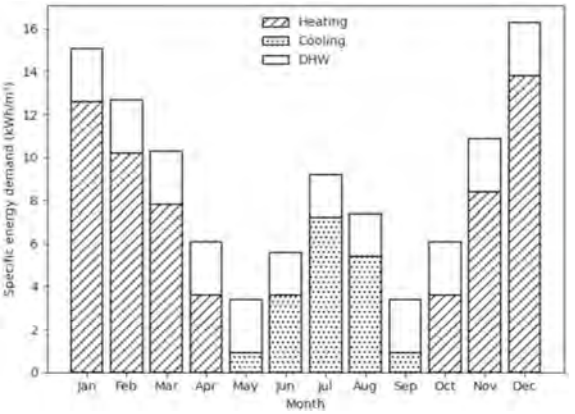


Fig. 2. Specific energy demand of the building.

Cooling loads are typically more continuous and evenly distributed than space heating and DHW demand, allowing modulating heat pumps to follow the load without intermediate storage. Fan-coil and radiant ceiling or wall systems have low water content and fast dynamic response, making direct operation straightforward. Therefore, cooling is handled directly by the heat pumps, without the use of TES.

An alternative configuration based on a single large heat pump covering heating, DHW, and cooling—with or without dedicated TES for cooling—was evaluated but rejected due to the need for complex hydraulic switching and priority management between operating modes, increased condensation risk, and higher operational vulnerability. Introducing TES specifically for cooling would further increase investment and complicate control, while providing only marginal energy benefits.

The system is therefore designed with two heat pumps operating in cascade, which improves part-load efficiency, reduces cycling, and enhances operational reliability. Under typical winter conditions, one unit satisfies the building's heating and DHW demand, while the second is activated only during extreme peak loads. In summer, the units operate in parallel, with one providing cooling and the other handling DHW production, enabling simultaneous operation without complex hydraulic switching or dedicated heat-recovery arrangements.

3 Results and Discussion

Scenario A. The fan-coil–based emission system was analyzed under continental climate conditions using seasonal performance factors typical of medium-temperature air-to-water heat pump operation. SCOP values of 3.4 (space heating) and 3.0 (DHW), and

a SEER of 4.0 (space cooling) were adopted, consistent with literature values for similar systems [16, 17] under part-load operation in continental climates.

With TES implemented, the total annual electricity consumption amounts to 31.5 kWh/m^2, with space heating, DHW preparation, and space cooling accounting for approximately 56%, 30%, and 14% of the total demand, respectively. In the absence of TES, electricity consumption increases to 35.8 kWh/m^2 due to reduced effective seasonal performance during peak heating and DHW operation. The integration of TES results in annual electricity savings of 13.7% for heating and DHW, corresponding to 12.9% when space cooling is included in the total electricity balance.

Scenario B. The low-temperature radiant (floor, wall, or ceiling) emission system was evaluated assuming improved seasonal performance due to lower supply temperatures in heating mode and higher chilled-water temperatures in cooling mode, with SCOP values of 4.0 for space heating and 3.1 for DHW preparation, and a SEER of 4.5 for space cooling, consistent with literature values for similar low-temperature systems.

When TES is applied, total annual electricity consumption is reduced to 28.1 kWh/m^2, with approximately 53% attributed to space heating, 32% to DHW preparation, and 15% to space cooling. Without TES, annual electricity consumption increases to 31.5 kWh/m^2, primarily due to reduced seasonal efficiency during simultaneous heating and DHW operation. The resulting electricity savings amount to 12.4% for heating and DHW, or 10.8% when cooling is included in the overall electricity demand (Fig. 3).

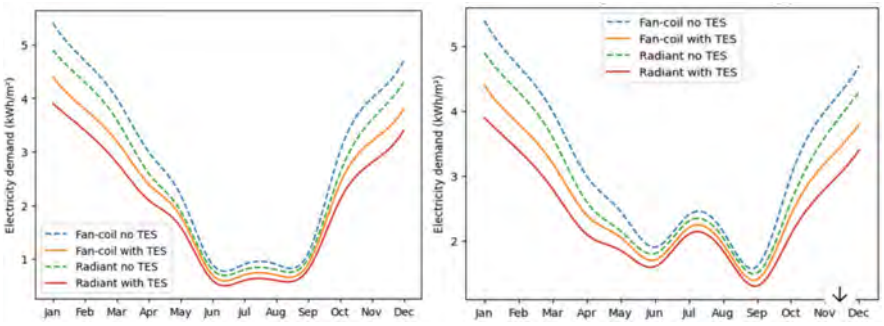


Fig. 3. Seasonal electricity demand profiles for (a) space heating and DHW and (b) space heating, DHW, and cooling, for fan-coil and radiant systems with and without TES.
Interpolated from monthly values using a third-order spline.

The radiant emission system exhibits lower absolute electricity consumption in both configurations, reflecting improved heat pump efficiency under low-temperature operating conditions. However, the relative impact of TES is comparable in both systems, indicating that its effectiveness is not limited to a specific heat-emission technology. TES was primarily dimensioned to support DHW preparation, as DHW demand is characterized by high supply temperature requirements, pronounced short-term peak loads, and a strongly intermittent daily consumption profile. By decoupling heat production from consumption, TES enables longer and more stable operation, resulting in improved effective seasonal performance, particularly for DHW preparation. Additional benefits

are observed for space heating through peak load shaving during cold periods. This reduction in coincident peak demand directly influences heat pump sizing by lowering the required design heating capacity and mitigating oversizing driven by simultaneous DHW and space heating loads, thereby enabling more balanced and efficient operation. In both scenarios, space cooling represents a relatively small share of annual electricity consumption but remains the determining factor for installed cooling capacity, while the benefits of TES are primarily associated with improved winter operation.

4 Conclusions

This study assessed the impact of short-term thermal energy storage on the electricity consumption and operational performance of HP systems coupled with fan-coil and low-temperature radiant emission systems. The integration of relatively small-volume TES—requiring limited additional space and no cooling storage—leads to significant reductions in annual electricity consumption, reaching 13.7% (12.9% including cooling) for the fan-coil system and 12.4% (10.8% including cooling) for the radiant system. These results confirm the effectiveness of TES across different heat-emission technologies while maintaining a simple heat pump configuration.

TES primarily enhances winter operation by reducing peak loads and improving the seasonal performance factor of the HP, with the most pronounced benefits for domestic hot water preparation due to its high-temperature requirements and intermittent demand profile. Although space cooling accounts for a minor share of annual electricity consumption, it governs installed cooling capacity, whereas TES benefits are mainly associated with heating and DHW operations. Additional improvements may also be achieved through the integration of rooftop photovoltaic systems, which align well with cooling demand and could further reduce grid electricity use while enabling a hybrid renewable-based HP system without modifying the core system architecture.

Due to the simplified monthly approach and Belgrade-specific conditions, the quantitative results may vary for other climates and building typologies, although the overall trends remain broadly applicable. Future work should therefore address dynamic validation, techno-economic feasibility, and implementation constraints to further substantiate the practical deployment potential of the proposed configurations.

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Retrofit of Large-Glazed University Buildings: A Comparative Energy Assessment in Thessaloniki and Naples

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Abstract. The energy performance of glazed façades is a central issue in the renovation of RC university buildings of sixties and seventies, many of which were constructed with large window-to-wall ratios and limited thermal or visual efficiency. Up-grading obsolete glazing represents a key opportunity to enhance indoor environmental quality while reducing energy use. This study investigates the impact of alternative glazing retrofit solutions on energy efficiency, and daylight availability in two offices within two university buildings, hosting mechanical engineering departments of two Institutions located in Mediterranean climates: Thessaloniki (Greece) and Naples (Italy). The dual-site approach allows an assessment of how different solar radiation patterns and climatic conditions affect the performance of advanced glazing systems. The research focuses on replacing existing low-performance windows with five high-efficiency products: low-emissivity double glazing, reflective glazing, spectrally selective glazing, and building-integrated photovoltaic (BIPV) glazings. Dynamic energy simulations are conducted to quantify changes in heating and cooling needs, as well as in lighting energy demand across various design scenarios. A strong dependence on the façade orientation and thermal, solar properties of the glass emerged. In both offices, the installation of transparent photovoltaic glass is the best option, although the g-value and visible transmittance slightly differ. This finding is interesting because glass of this type, characterized by high g-values, can play an important role in buildings without cooling systems under the current climate change and extreme heat waves. Overall, the work highlights the relevance of informed façade design choices in balancing energy use, daylight performance, visual comfort, and operational energy use during deep renovation processes.

Keywords: Energy Efficiency · University Buildings · Glazed Façades · High-Efficiency Windows · Mediterranean Climates

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1 Introduction

European reinforced concrete (RC) buildings built starting from sixties are generally characterized by poor energy performance [1], mainly because they were built before the introduction of any European directives addressing energy efficiency in the construction sector. When shifting the attention from European to national scales this trend is confirmed. For example, in Italy, the first laws on energy saving date back to 1976 [2] and 1991 [3]. In Greece, the first regulation setting thermal transmittance limits for opaque building components was adopted in 1979 [4], while only in 2010 with the KENAK regulation [5] a comprehensive approach to the whole building system, including active-energy systems, was adopted.

University buildings built in the same period are characterized by similar shortcomings, and, moreover, they are typically characterized by high window-to-wall ratios (WWR), which further exacerbate the energy inefficiency of the building [6]. In such cases, the selection of appropriate type of glass [7] becomes essential to limit heat losses in winter and solar gains in summer, to ensure adequate thermal and visual comfort for occupants and avoid an excessive use of heating and cooling systems.

Although the use of large glazed surfaces, continuous window strips, curtain walls, and modular facades is a typical architectural feature of buildings from the 1960s and 1970s, limited – if any – consideration was given to the energy performance. Consequently, the energy retrofit of the transparent building envelope offers significant potential to improve the indoor environmental quality – including IAQ, thermal, visual, and acoustic comfort – while simultaneously enhance the energy efficiency of the building through the reduction of energy demand and related pollutant emissions.

In this study it is proposed the energy improvement of the transparent envelope in two university office zones located in building hosting the mechanical engineering departments of the Aristotle University of Thessaloniki, in Greece, and of the University of Naples Federico II in Italy. Alternative glazing retrofit solutions, characterized by different thermal transmittance (U-value), solar heat gain coefficient (SHGC), and visible transmittance, are investigated in order to identify the optimal glazing configuration for enhancing the building energy performance.

2 Case Studies

The analysis is conducted on two single offices that belong to Building A and Building B (Fig. 1), located in Thessaloniki and Naples, respectively. Building A is detailed described in [8], here the main architectural and thermo-physical characteristics of the buildings, including the thermal transmittance values for opaque and transparent components, and the intended uses, are summarized in Table 1. Building B, in Naples, was built between 1956 and 1965. It has a reinforced concrete structure and the main thermophysical properties are listed in Table 1.

A model of both buildings was created in the DesignBuilder environment [10] (Fig. 1), which serves as a graphical interface for the EnergyPlus [11] dynamic energy simulation engine, and the offices to be investigated were detailed characterized.



Fig. 1. Building under investigation and energy models in DesignBuilder®: Thessaloniki (A), Naples (B)

Table 1. Main data for buildings under investigation

	Building A	Building B
Location	Thessaloniki, Greece	Naples, Italy
Number of floors	Nine, total height = 27 m	Twelve, total height = 54.7 m
Intended uses	Offices, secretariats, laboratories	Classrooms, offices, secretariats, laboratories
U wall [W/m^{2}K]	0.71	0.89
U roof [W/m^{2}K]	0.77	1.00
U floor on the ground [W/m^{2}K]	3.11	0.92
U window [W/m^{2}K] g-value	2.82 0.64	3.2 0.76
Weather data	Thessaloniki-Makedonia TMY 2009–2023*1	Napoli Capodichino TMY 2009–2023*1

*1 available on [9]

Specific data for the investigated offices – that will be referred as office A and office B – such as the area, location, exposure, WWR for the façade externally exposed, and internal gains are reported in Table 2.

Concerning energy demand for heating and cooling, the thermal needs were evaluated for both offices in order to avoid a strong dependence of the results on the specific system used for microclimatic control, since the main objective of the study was to assess the effect of the different window typologies. Regarding the operation period, in Italy, the heating season is regulated by DPR 412/93, according to which for a climatic zone C, such as Naples, the heating period goes from 15 November to 31 March with a maximum operation time of 10 h per day, and a heating setpoint of 20 °C. No regulations exist for the cooling season, therefore it was considered from 15 May to 30 September, with a cooling setpoint of 26 °C. In Greece, there are no regulations for both heating and cooling seasons, so the same operating periods adopted for Italy were considered, with a different heating setpoint set at 21 °C [8].

Table 2. Geometry and internal gains data for the case studies

	Office A	**Office B**
Area [m^2]	21.99	18.25
Location	8^{th} floor	11^{th} floor
Exposure	North	West
WWR [%]	57	57
Occupation [p/m^2]	0.1*	0.11*
Lighting [W/m^2] with daylight control Desired illuminance [lux]	14* 500	4* 400
Equipment [W/m^2]	15*	30*

* The values for occupancy, lighting, and equipment reported in the table represent nominal values; appropriate schedules reflecting typical office use were applied. In detail, buildings are occupied for 10 h per day (8:00–18:00), five days per week. The use of equipment is aligned with occupancy, with reduced values during unoccupied hours due to standby operation. Both the value and schedules are representative of the realistic use of the two offices.

2.1 Energy Efficiency Measure: Glazing Configurations

Five glazing configurations for improving the energy performance of the two offices were tested. The corresponding thermal and solar properties are listed in Table 3.

With reference to thermal transmittance, the configurations are characterized by U-values in a narrow range – from 1.6 to 2.0 W/m^2K – with the best performance achieved by the double spectrally selective glazing and the BIPV options, while the lowest performing is the double reflective glazing. In any case, all the selected windows are characterized by a lower thermal transmittance value compared to the base case (Table 1), so an effect on the energy demand is expected.

Conversely with reference to the solar and visible optical properties, the tested glazing configurations are characterized by different values. Double low-e glazing is characterized by the highest solar heat gain coefficient and visible transmittance, whereas

Table 3. Main thermal and solar properties of testes window configurations

Description	U-value [W/m^{2}K]	g-value [−]	Glass visible transmittance [−]
Double low-e	1.69	0.63	0.721
Double reflective	2.01	0.13	0.073
Double spectrally selective	1.63	0.42	0.682
BIPV – option 1	1.60	0.17	0.30
BIPV – option 2	1.60	0.09	0.10

reflective and BIPV options provide the strongest solar control. Moreover, BIPV configurations offer electricity conversion potential. Spectrally selective option is a compromise with reference to both solar and visible properties.

3 Analysis of Results

A comparison of the thermal needs for heating and cooling, as well as the lighting energy demand under the tested window configurations for the two offices, is shown in Fig. 2A and B for Thessaloniki and Naples, respectively. The solar heat gains through windows are also reported and shown on the right vertical axes. The percentage variations in heating and cooling needs are summarized in Table 4.

To correctly discuss these results, it is necessary to underline some important differences between the two investigated offices. The main difference concerns the façade orientation, office A is north-facing, while office B is west-facing. This aspect strongly affects the role of window properties.

For north-facing environments, thermal transmittance is dominant, while g-value has a limited influence because north-facing facades are mainly interested by the diffuse solar radiation, and a limited direct solar exposure. In contrast, for west-facing orientation, the solar direct effect is dominant, with a significant impact especially in the afternoon hours. This is clearly visible in the solar heat gains shown in Fig. 2. This difference directly affects daylight availability, artificial lighting use, and heating and cooling requirements.

In office A, all glazing configurations allow a reduction in heating need. This is due to the lower thermal transmittance value, which as previously discussed, strongly affect the north-facing environments. The effect on cooling need is minimal, and only two configurations result in a slight reduction.

In office B, glazing configurations with low g-values significantly reduce cooling need. Heating demand is also affected by variations in solar heat gains, while internal gains, such as lighting, have only a minor effect.

To illustrate the effect of solar gain on cooling need for the investigated orientations, Fig. 3A shows the relationship between g-value and cooling need. A strong influence on western exposure office in Naples is highlighted, while for the north-facing exposure in Thessaloniki the curve is nearly flat, indicating limited dependence.

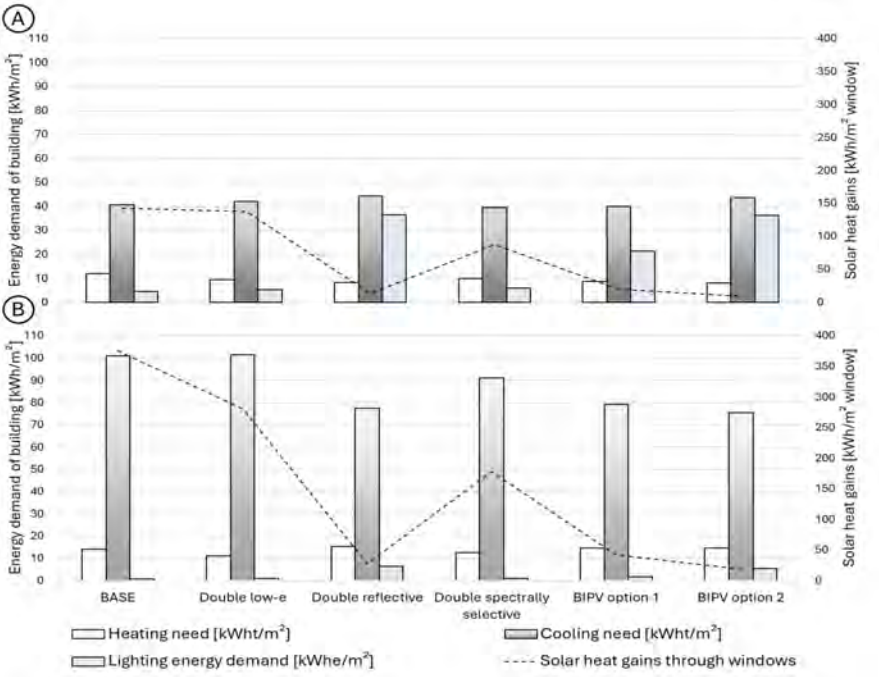


Fig. 2. Heating and cooling needs, lighting energy demand and solar heat gains under the tested window configurations: office A in Thessaloniki (A) and office B in Naples (B).

Table 4. Percentage variations in heating and cooling needs.

	Percentage variations [%]			
	Office A - Thessaloniki		Office B - Naples	
	Heating	Cooling	Heating	Cooling
Double low-e	−20.4%	3.4%	−21.5%	0.5%
Double reflective	−29.6%	9.0%	9.3%	−23.4%
Double spectrally selective	−17.0%	−2.8%	−11.6%	−9.9%
BIPV – option 1	−27.0%	−1.5%	3.5%	−21.5%
BIPV – option 2	−32.4%	7.7%	3.5%	−25.4%

It is furthermore interesting to observe the relationship between the visible transmittance of glass and the lighting energy demand, illustrated in Fig. 3B. All the tested glazing configurations are characterized by a lower visible transmittance compared with base configuration. This increases lighting demand, more pronounced in office A in Thessaloniki, with a limited daylight availability.

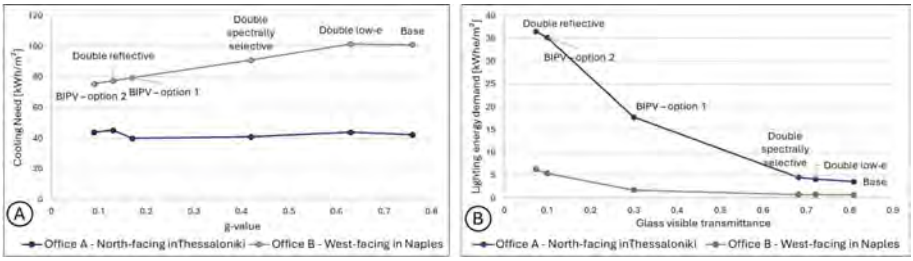


Fig. 3. Relationship between g-value and cooling need (A), relationship between glass visible transmittance and lighting energy demand (B).

Overall, both offices show a higher cooling need than the heating one. This is due to the intended use and the high internal gains, mainly related to office equipment, operating during occupied hours when specific indoor thermal comfort conditions are required. For this reason, the selection of the optimal window glazing configuration is cooling oriented, and for both offices the best option is BIPV.

Specifically for office A, north-facing in Thessaloniki, BIPV option 1 is the most suitable solution, with a reduction of around 27% and 1.5% for heating and cooling needs, respectively. It is characterized by the lowest thermal transmittance value, and in addition, it has a medium visible factor, which limits the increase in lighting energy demand compared with the other solutions, and a relatively low g-value, although its effect is less relevant for north-facing exposure. Finally, it also provides electricity conversion, even if low, because of the low efficiency and peak power of transparent building-integrated photovoltaics, of around 9.7 kWh/m^2 of window surface. Double spectrally selective is also effective.

For office B the most suitable solution is BIPV option 2. This configuration allows the highest reduction in cooling need, approximately 25.4%, and a limited increase in heating need of around 3.5%. Despite the slight increase in lighting demand, the reduction in solar gains is predominant in both seasons, with beneficial effect in summer and a negative impact in winter. As for electricity conversion, BIPV 2 technology, which is darker than BIPV 1 (with a lower g-values and visible transmittance), enables a conversion of approximately 20 kWh/m^2 of window area, also because of the west-facing exposure.

3.1 Investigation of an Office Without Cooling System

These results could be particularly relevant for buildings without cooling systems. A preliminary analysis was conducted for the office in Naples by comparing indoor air temperature trends during a typical summer week in July with two configurations: the base case and by applying the best-performing window option, i.e., BIPV 2 (Fig. 4).

It emerged a reduction in peak indoor air temperatures of around 4–6 °C, further highlighting the importance of selecting appropriate window systems during retrofit interventions and demonstrating the impact on indoor thermal conditions. This aspect will be further investigated in future work.

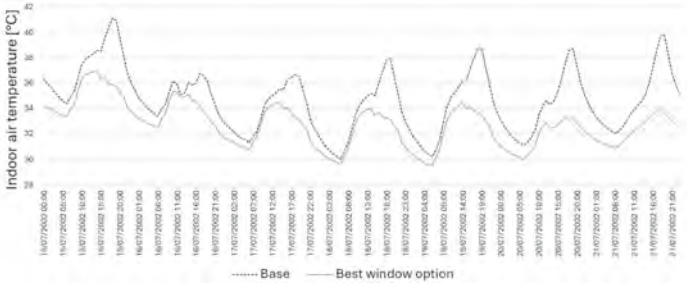


Fig. 4. Trends of indoor air temperature during a typical summer week in July for the office located in Naples: base configuration and best window.

4 Conclusions

The results highlight that glazing energy improvement requires an informed design approach, where the façade orientation plays a key role in retrofit effectiveness.

For north-facing façade, the thermal transmittance is the dominant parameter, with a significant effect on the heating need. West-facing facade is primarily influenced by the g-value, which has a strong effect on the cooling need. Visible transmittance highly affects lighting energy demand, and consequently influences both heating and cooling needs, and therefore needs to be properly considered.

Main finding in this study is that transparent BIPV solutions are the optimal ones for both orientations, although with different solar factors and visible transmittance values. For office A, located on the north-facing façade of the building in Thessaloniki, the optimal choice is mainly driven by the U value. For office B, located on the west-facing façade of the building in Naples, the selected BIPV is characterized by the lowest g-value, around 0.09, which strongly reduces the solar heat gains, demonstrating that these devices can effectively act as solar control systems besides the electricity conversion. In addition, these systems can be useful in buildings without a microclimate control system for cooling, helping to reduce peak air temperatures.

It should also be noted that thermal and visual parameters are sensitive to the climatic context, considering phenomena not always directly correlated, such as outdoor temperature, solar radiation, day length, and natural and artificial lighting availability. Climatic and cultural aspects, including university schedules and examination periods, also influence the results. Therefore, specific studies are needed for different climatic contexts and boundary conditions, since economic, energy, and environmental outcomes may vary.

Overall, the study underlines the importance of informed façade design choices during deep renovation processes, which results particularly relevant for buildings without cooling systems where a mitigation of indoor overheating could be achieved.

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Influence of Design Parameters on the Energy Performance of Opaque Ventilated Facades

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Abstract. Opaque Ventilated Facades (OVFs) present a sustainable cooling solution for buildings in the Mediterranean area. Their proper design, however, is essential to achieve maximum benefits from their installation. In this study, a validated dynamic insulation OVF (DIOVF) model built in EnergyPlus whole-building simulation tool is used to examine the influence of key façade elements on its energy performance. In particular, three design parameters—the vent opening area, the cavity width, and the addition of a reflective/low-emissivity coating in the cavity—are examined with respect to their influence on the energy performance of a 3 m height DIOVF installed on the west façade of a free-running test-cell during a typical summer day in the city of Thessaloniki, northern Greece. The results of the study indicate that larger vents reduce total heat gains by 14%, while testing the cavity width parameter revealed that the highest heat reduction occurs between the 5 cm and 10 cm cavities. Finally, the low-emissivity coating is favorable especially for narrower cavities.

Keywords: Opaque Ventilated Facade · Dynamic Insulation · Airflow Network · EnergyPlus · Reflective/Low-emissivity Coating

1 Introduction

A primary European target as captured in the Energy Performance of Buildings Directive (EPBD) is the achievement of a zero-emission building stock by 2050 [1]. Since the building envelope is responsible for an important share of the total heating and cooling energy needs a building has, several building envelope technologies have been developed over the last decades, aiming at elevating a building's energy performance. Opaque Ventilated Facades (OVFs) can offer natural cooling to a building in mild-hot climates like the Mediterranean one, while depending on their stratification and thermal characteristics, their efficiency varies [2]. Moreover, dynamic insulation (DI) technologies rely on the adjustment of the envelope's thermal resistance on the prevailing climatic conditions [3]. During the cooling period, DI systems lower their thermal resistance when the heat flux moves outdoors (cooler ambient environment), while they increase their thermal resistance when the heat flux tends to move indoors (hotter ambient environment). Combining the OVF and the DI concepts into a Dynamic Insulation Opaque Ventilated Façade (DIOVF) seems to offer improved benefits to a building [4]. Such a system is an

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OVF with a main difference, though, from conventional OVFs: the insulation layer is installed on the external side of the ventilated cavity to increase heat losses during vent opening hours.

Key parameters that affect the energy performance of any OVF and consequently of the DIOVF are the vents' opening area, the cavity width, and the emissivity of the cavity walls. So far, the impact of the implementation of a low-emissivity/high reflectivity coating in cavities has been mainly tested in roof applications [5], and inadequately in ventilated facades. From the limited number of studies existing on this topic, it was concluded that although such a coating efficiently reduces the heat gains during daytime, it reduces the heat losses during nighttime, making unclear whether its implementation is beneficial or not [6].

In this study, the influence of the vents' opening area, the cavity width, and the emissivity of the internal cavity wall on the DIOVF system's cooling energy performance is tested in an already developed and validated Airflow Network (AFN) model in EnergyPlus.

2 Materials and Method

2.1 Description of the DIOVF System

The DIOVF system examined in this study is depicted in Fig. 1, and its material stratification is presented in Table 1.

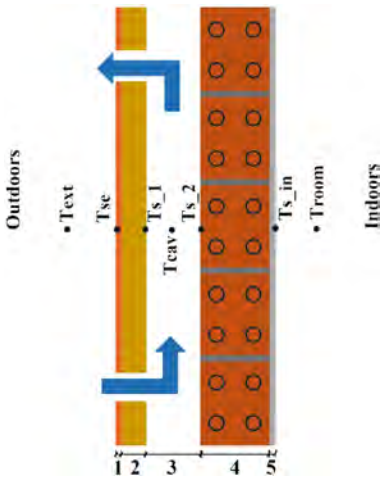


Fig. 1. View of the examined DIOVF system and the nodes for which the results were derived.

The system, having a 3 m height, was implemented on the west façade of an ideal free-running test-cell, as this orientation experiences the highest thermal loads during the summer. Since the study uses the climatic conditions of Thessaloniki, Greece, both the west façade (featuring the DIOVF) and the remaining facades were designed to meet

the maximum allowable U-value of the Greek regulation [7], which is 0.4 W/[m^2 × K)]. Specifically, the U-value of the DIOVF was 0.37 W/[m^2 × K)], while the other facades, consisting of masonry with perforated clay bricks and XPS thermal insulation, had a U-value of 0.4 W/[m^2 × K)].

Table 1. DIOVF material composition with reference to Fig. 1.

Layer	Material	Thickness [m]	Thermal conductivity [W/(m × K)]
1	Ceramic tiles	0.012	1.05
2	Rock wool panels	0.07	0.035
3	Air cavity	Varies	–
4	Masonry (perforated clay bricks)	0.18	0.58
5	Lime-cement plaster	0.02	0.87

Regarding the inlet and outlet vents, a high thermal resistance option was chosen after conducting market research; when closed, they feature a thermal resistance equal to 2.2[m^2 × K)]/W. Since their actual airtightness is unknown, their air permeability was considered according to Class 1 of EN 12207 [8].

According to a previous study [4], a good practice for Thessaloniki's region is to keep the vents open from 20:00 to 8:00, so this approach was adopted here. The same representative week (10/7–14/7) was also considered here, from which the 11th of July was selected to analyze the results.

The parameters examined in this study are:

a) The vents opening area, where two cases were tested for a 5 cm cavity width: large vents (L) with a total area of 1m^2 (0.1 m height × 10 m length), and medium vents (I) with a total area of 0.6m^2 (0.06 m height × 10 m length). Both opening areas are large enough to consider the air cavity fully ventilated according to the Greek regulation [7].
b) The cavity width, where three cases were tested: 5 cm, 10 cm, and 15 cm, and
c) The thermal emissivity of the internal cavity wall, with the existence (R) or not (N) of a low emissivity coating. In the N case the thermal absorptance of the internal cavity wall was 0.9, while in the R case a 0.1 thermal absorptance was considered.

2.2 Simulation Approach

The simulation approach followed in this study includes EnergyPlus and its integrated Airflow Network (AFN) model. The DIOVF model has been already developed and validated against the experimental results presented in [2].

The AFN model is based on Walton's AIRNET model [9]. The thermal zones and the ambient environment are simulated with nodes which are connected through airflow linkages [10]. The calculation process followed by the AFN involves an initial computation of airflow and pressure, followed by node temperatures and humidity, with the final

step quantifying sensible and latent loads. While AFN is less precise than CFD, using 0D node and 1D airflow calculations, the results remain sufficiently accurate.

According to the existing literature, subdividing the ventilated façade into three stacked zones, keeping the two extreme as small as the vents opening, is necessary to achieve the optimum precision when the AFN simulation approach is used [11].

Convection is the dominant heat transfer mechanism when vents are open, so to better account for it, the adaptive convection algorithm was used for the internal surface convection calculations, which selects for each timestep the most appropriate convection model for each surface [12].

3 Results and Discussion

3.1 Boundary Conditions

The 11th of July was selected as a representative day for Thessaloniki, for which the dry-bulb temperature (Text) and the incident solar irradiance on the examined façade (Isol) are depicted in Fig. 2. This day has an average Text equal to 26.6 °C, a minimum Text equal to 21.4 °C, and a maximum Text equal to 31.5 °C. From the Isol illustration it becomes obvious that the DIOVF accepts the maximum incident solar irradiance (706 W/m^2) at 17:00, which is reasonable for a west oriented façade, while prior to 13:00 it receives a very small solar irradiance fraction.

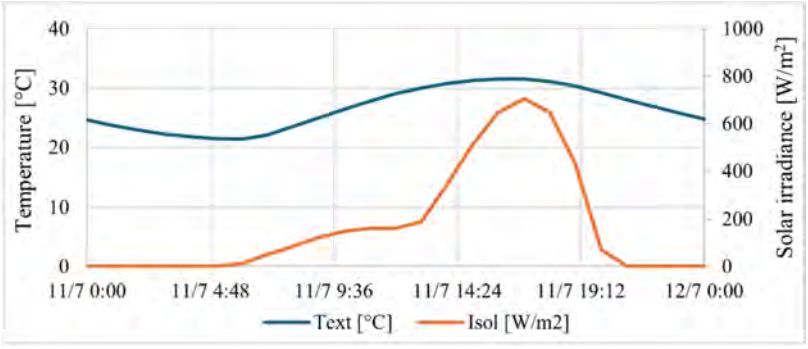


Fig. 2. Text and Isol for the 11th of July.

The wind conditions of the examined day are presented in Fig. 3. During the night, the wind is light, reaching a maximum speed of 3 m/s mainly with a south-east direction, while during the day, when the vents are closed, the wind remains relatively light with maximum value reaching 5 m/s. Its direction varies from south-west early in the morning to south-east in the afternoon.

3.2 Effect of Vents Opening Area

The first parameter examined was the influence of the vents' opening area on the façade's efficiency. To properly compare the two cases, the heat flow on the wall surface facing

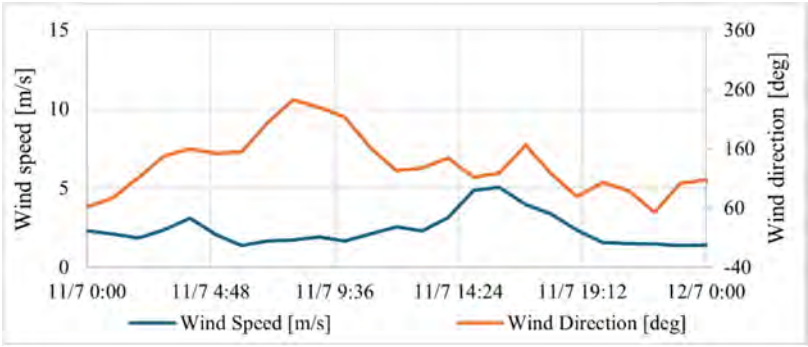


Fig. 3. Wind speed and wind direction for the 11th of July.

the room was considered. The results are presented in Table 2, where negative values indicate an outward direction of the heat flow, while a positive value indicates heat gains for the test-cell.

Table 2. Heat flow on the wall surface facing the room for the 11th of July.

Case	Day [Wh/m^2]	Night [Wh/m^2]	Total [Wh/m^2]
L	−14.6	23.1	8.5
I	−13.8	23.5	9.7

It can be observed that during daytime, heat losses for the room are dominant, while during nighttime heat gains are prevailing. This trend is related to the wall's thermal mass and the façade's west orientation. The vents open at 20:00, but the heat gains for the room start reducing from 3:00. Similarly, the vents close at 8:00, while the heat gains for the room begin to increase from 15:00.

From the results, it becomes evident that a larger opening area corresponds to increased heat losses, whereas the heat gains between the two cases are similar. In total, the larger opening area is more favorable as it results in 14% less total heat gains for the adjacent room.

3.3 Effect of Cavity Width

Since L vents were more effective, different cavity widths were tested only for L vents. In Table 3 the heat flow results are presented for the three cavities studied.

Increasing the width of the DIOVF's cavity corresponds to reduced heat gains for the room, which is mostly related to the increased heat losses. From the 24 h results it can be observed that having as a reference the 5 cm façade, in the 10 cm façade there is a 59% reduction in the total heat gains, while for the 15 cm façade there is a 91% reduction of the total heat gains.

Table 3. Heat flow on the room's surface for the 11th of July for the examined cavity widths.

Cavity width [cm]	Day [Wh/m^2]	Night [Wh/m^2]	Total [Wh/m^2]
5	−14.6	23.1	8.5
10	−17.8	21.4	3.5
15	−19.6	20.4	0.8

Table 4 presents the maximum net volume flow rate (NVFR) for all three cases, along with the maximum net airflow velocity (NAV) recorded in each cavity. These maximum values for all three cases occurred at 4:00, coinciding with the maximum wind speed during the vents' opening hours.

Table 4. Peak net airflow rate and velocity for the cavities tested at 4:00, July 11th (N case).

Cavity width [cm]	Max. NVFR [m^3/s]	Max. NAV [m/s]
5	0.14	0.28
10	0.2	0.2
15	0.21	0.14

The results in Table 4 provide a more clear view of the results in Table 3. There is an important increase in the volume airflow rate in the 10 cm façade, which explains why the shift from 5 cm to 10 cm affects more the façade's efficiency.

Moreover, Fig. 4 depicts Ts_2 temperatures for the three cavity widths. It can be observed that both during nighttime and daytime the temperature difference between 5 cm and 10 cm is greater than that between 10 cm and 15 cm.

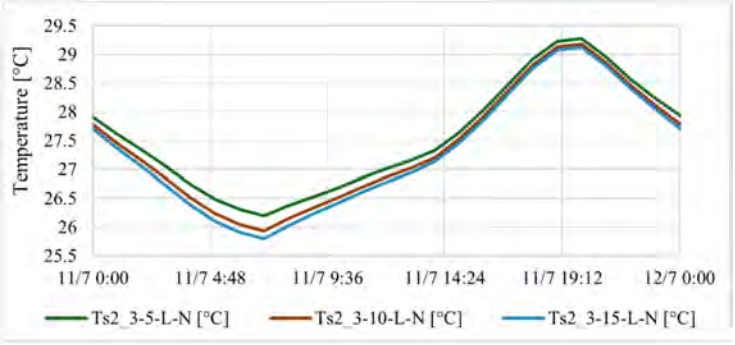


Fig. 4. Ts_2 temperature profile for the 5, 10, 15 cm cavities on July 11th (N case).

3.4 Effect of cavity's Emissivity

Table 5 provides the heat flow results for the low-emissivity coating addition on the internal cavity surface, and Fig. 5 depicts Ts_2 temperatures for all the cavity widths.

Table 5. Heat flow on the wall surface facing the room for the 11th of July for the three cavity widths with a low-emissivity coating (R case).

Cavity width [cm]	Day [Wh/m^2]	Night [Wh/m^2]	Total [Wh/m^2]
5	−13.7	19.6	5.9
10	−16.6	17.9	1.3
15	−18	17	−1.0

Comparing Table 3 with Table 5 and Fig. 4 with Fig. 5 it becomes evident that the addition of a low-emissivity coating improves the cooling performance of the DIOVF. Despite the slight reduction in heat losses in the R case – due to the low emissivity of the coating, which limits the radiation exchange of the warmer inner wall with the colder outer skin during nighttime – the material's high reflectivity significantly reduces the thermal loads transferred from the exterior to the interior during the day, especially in the narrower cavities which have the lowest heat losses at night.

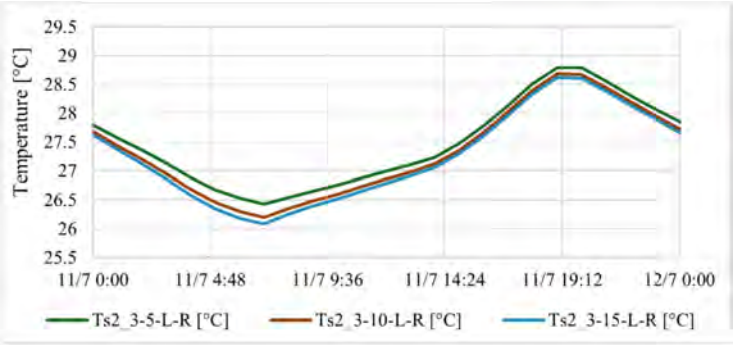


Fig. 5. Ts_2 temperature profile for the 5, 10, 15 cm cavities on July 11th (R case).

4 Conclusions

The study presented a simulation-based analysis of key design parameters (vents' opening area, cavity width, and emissivity of the internal cavity wall) influence on the summer energy performance of a DIOVF system for Mediterranean climate conditions (a typical climatic file for Thessaloniki, Greece was used). The analysis was conducted on a validated AFN model in EnergyPlus ensuring results' precision.

The results revealed that a larger vent area increases heat losses, resulting in approximately 14% lower total heat gains and improved system's cooling capacity. Moreover, the analysis indicated that increasing the cavity width from 5 cm to 10 cm leads to an absolute heat load reduction almost double than that of increasing the width from 10 cm to 15 cm. Despite this, the wider cavity remains the one leading to the optimum system's cooling performance.

The addition of a low-emissivity/high reflectivity coating on the internal cavity wall proved to be beneficial for all cavity widths examined. Due to the material's low emissivity, which limits radiation exchange with the opposing wall, it efficiently decreases daytime heat gains, though at the same time it reduces to a smaller percent the heat losses during nighttime. That is why its addition is more favorable to narrow cavity facades, which feature lower heat losses at night due to lower airflow rates.

Future analysis could focus on different system configurations, featuring alternative construction materials to further evaluate the influence of these parameters on its energy performance. It would also be meaningful to test these variations under various climatic conditions to obtain a clear view of the system's full cooling capacity.

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Energy Analysis of Brazilian School NZEB Building Considering the Impact of Climate Change

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Abstract. The energy transition is one of the required paths to mitigate global warming. Buildings are among the largest consumers of energy. Net Zero Energy Buildings (nZEB) are designed to be highly efficient. The goal of an is to achieve a net-zero energy footprint by balancing the annual energy consumed with the renewable energy produced on-site. However, the Energy Source Availability (solar or wind) may be affected by climate change. Thus, this work aims to perform an energy analysis of a typical Brazilian nZEB school building by comparing its energy demand with its photovoltaic energy generation in a future moderate scenario (IPCC SSP-4.5 2050). For this purpose, a Brazilian representative school archetype was designed in EnergyPlus software, equipped with PTHP (Packaged Terminal Heat Pump) systems for heating or cooling and photovoltaic systems capable of generating the required energy. A total of 24 Brazilian cities were chosen to execute the simulations, representing 12 bioclimatic zones. The results show that The Energy Demand grows as the cooling demand increases. The electrical annual intensity (kWh/m^2) has increased on average by 14%, and the annual photovoltaic energy generated decreased by about 1.4%. The worst result is in Campo Grande, MS, where energy demand increased about 24% and photovoltaic energy generation decreased by 12%. It is evident that tailoring nZEB definitions to balance energy supply and demand is vital. Overall, the findings emphasize the importance of adaptive design strategies and continuous innovation to maintain the effectiveness and resilience of nZEBs as climate patterns change.

Keywords: Global Warming · Sustainable Energy Transition · Photovoltaic Generation · Energy Demand · Sustainable Buildings

1 Introduction

Climate change and energy are linked by the role of fossil fuel greenhouse gas emissions. The energy transition is one of the required paths to mitigate global warming. The gradual increase in the use of renewable energy has reduced greenhouse gas emissions and enhanced carbon sequestration [1, 2]. Buildings are among the largest consumers of energy, accounting for nearly 30% of final global energy consumption and 26%

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of global energy-related emissions [3]. This significant energy demand highlights the importance of improving building energy efficiency and utilizing renewable energy to reduce emissions and support global energy transitions. Net Zero Energy Buildings (nZEB), also known as Nearly Zero Energy, are designed to be highly energy efficient [4–7]. They also generate the energy they need from renewable sources such as solar or wind. The goal of an nZEB is to achieve a net-zero energy footprint by balancing the annual energy consumed with the renewable energy produced on-site [8–11]. However, the availability of solar radiation or wind may be affected by climate change [5, 12] . Bioclimatic zones provide a framework for classifying the climatic characteristics of regions worldwide. Therefore, it is important to investigate the impact of climate change on the renewable energy systems integrated into nZEB buildings. Thus, this work aims to perform an energy analysis of a nZEB school building by comparing its energy demand with its photovoltaic energy generation under a future moderate climate scenario across different bioclimate Brazilian zones.

2 Materials and Methods

For this purpose, methodological steps were outlined: characterization of the systems, creation of the weather archives, energy simulation of the school for current and future scenarios, and lastly, the quantification of energy consumption and generation for current and future scenarios.

Energy simulations were performed using EnergyPlus software, which employs a dynamic calculation methodology. This approach enables the simulation results to be representative of real building thermal and energy performance conditions.

A representative Brazilian school building archetype (Fig. 1) was modeled based on the typology described in [13]. The building is equipped with packaged terminal heat pump (PTHP) systems for heating and cooling, as well as photovoltaic systems designed to generate the required on-site energy. Internal heat gains were primarily associated with occupancy and electrical equipment. The photovoltaic system was designed using 650Wp modules. The numbers vary within a range of 139 to 229 modules facing North and tilted according to the latitude along a 765 m^2 rooftop area. The photovoltaic modules were oriented northward, as the building is in the Southern Hemisphere, and tilted according to the local latitude. The total building floor area is 1.566 m^2.

Weather files for the simulations were developed using historical data from the ERA satellite database, covering the period from 1985 to 2014, and future projections for 2050 based on the IPCC SSP4.5 moderate climate change scenario [14]. Simulations were conducted for 24 Brazilian cities representing 12 bioclimatic zones (see Table 1), as classified according to the Köppen–Geiger system and the Brazilian bioclimatic zoning framework [15]. The Köppen–Geiger climate classification is used worldwide and can serve as a reference for applying this work to other countries.

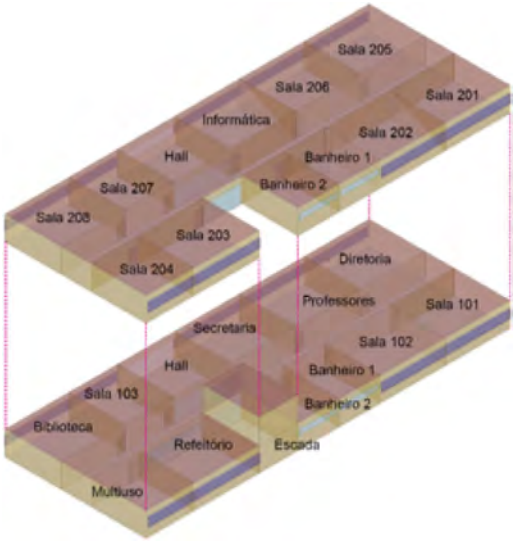


Fig. 1: Brazilian representative school archetype [13].

In this work, the total consumption of the building per year (MWh), the electrical annual intensity – I_E (kWh/m^2) and the annual photovoltaic energy generation (MWh) were simulated and analyzed. The relationship between the energy demand and generation was established using the percentage renewable energy supply index (RES), according to the Eq. (1).

$$RES_{\%} = \frac{E_{PV}}{E_C} \times 100 \tag{1}$$

where:

RES = Renewable energy supply index (%)

E_{PV} = Annual Photovoltaic Energy Generation (MWh);

E_C = Annual Energy Building Demand (MWh).

Table 1: Climate classification of Brazilian cities selected

K-G	BZ	City	Lat S(°)	Long W(°)	K-G	BZ	City	Lat S(°)	Long W(°)
Cwb	1 M	Campos do Jordão, SP	22.7	45.6	BSh	4A	Campina Grande, PB	7.3	35.9
Cfb	1 M	Curitiba, PR	25.4	49.3	Af	4A	Rio de Janeiro, RJ	22.9	43.2
Cfb	1R	Caxias do Sul, RS	29.2	51.2	As	4B	Arcoverde, PB	08.4	37.0
Cfb	1R	Urubici, RS	28.0	49.3	Aw	4B	Campo Grande, MS	20.4	54.6
Cwa	2 M	Juiz de Fora, MG	21.7	43.3	As	5A	Natal, RN	05.8	35.2
Cfa	2 M	São Paulo, SP	23.5	46.6	Am	5A	Salvador, BA	13.0	38.5
Cfa	2R	Pelotas, RS	31.7	52.3	BSh	5B	Janaúba, MG	15.8	43.3
Cfa	2R	Porto Alegre, RS	30.0	51.2	BSh	5B	Juazeiro do Norte, BA	07.2	39.3
Cfa	3A	Florianópolis, SC	27.6	48.5	BSh	6A	Fortaleza, CE	03.7	38.5
BSh	3A	Vitória da Conquista, BA	14.8	40.8	Aw	6A	Teresina, PI	05.1	42.8
Aw	3B	Brasília, DF	15.8	47.9	Aw	6B	Palma, TO	10.2	48.3
Aw	3B	Londrina, PR	23.3	51.1	BWh	6B	Petrolina, PE	09.4	40.5

3 Results

The results show that the energy demand grows, especially in hot and humid climates, with the cooling demand increasing.

Table 2 presents the annual total energy consumption of the building, the annual photovoltaic energy generation, and the percentage renewable energy supply index for each city for historic and future weather conditions.

The percentage of renewable energy supplied by the building is highlighted in Fig. 2, which shows nZEB buildings with unmet energy demand in the future scenario.

Considering all locations, the annual energy consumption increased by an average of 14%, while annual solar energy generation decreased by approximately 1.4%. The most critical case was observed in Campo Grande, MS, where energy demand increased by about 24% and photovoltaic energy generation decreased by 12%.

Table 2: Annual Energy Demand and PV Generation

City	E_C Historic (MWh)	E_C Future (MWh)	E_{PV} Historic (MWh)	E_{PV} Future (MWh)	RES % Historic	RES % Future
Campos do Jordão, SP	104.11	111.75	150.85	145.90	145%	131%
Curitiba, PR	109.86	111.33	105.83	97.80	96%	88%
Caxias do Sul, RS	141.13	132.96	132.52	130.44	94%	98%
Urubici, RS	138.36	126.45	117.52	112.60	85%	89%
Juiz de Fora, MG	118.80	135.21	152.87	152.27	129%	113%
São Paulo, SP	115.12	127.44	141.55	136.30	123%	107%
Pelotas, RS	123.48	121.92	123.65	116.01	100%	95%
Porto Alegre, RS	125.19	133.44	126.53	120.15	101%	90%
Florianópolis, SC	115.53	127.48	114.37	105.56	99%	83%
Vitória da Conquista, BA	121.28	141.19	187.16	192.21	154%	136%
Brasília, DF	121.67	144.69	204.85	206.15	168%	142%
Londrina, PR	134.48	158.40	151.01	147.06	112%	93%
Campina Grande, PB	160.29	192.41	220.06	222.83	137%	116%
Rio de Janeiro, RJ	156.27	180.51	152.74	148.08	98%	82%
Arcoverde, PB	156.26	188.50	241.20	245.08	154%	130%
Campo Grande, MS	168.48	208.24	191.26	168.48	114%	81%
Natal, RN	232.88	287.81	255.50	257.99	110%	90%
Salvador, BA	189.54	230.53	225.31	225.37	119%	98%
Janaúba, MG	165.71	199.25	235.51	242.19	142%	122%
Juazeiro do Norte, BA	180.77	215.01	234.60	239.23	130%	111%
Fortaleza, CE	239.81	286.94	273.53	278.63	114%	97%
Teresina, PI	258.39	316.39	237.65	247.15	92%	78%
Palma, TO	207.03	253.91	226.21	232.50	109%	92%
Petrolina, PE	212.11	254.66	241.37	249.19	114%	98%

The results indicate that, in hot climates, the increase in cooling demand led to higher overall energy consumption, and even when photovoltaic generation improved, the resulting energy balance remained negative. In contrast, colder climates exhibited better performance due to a reduction in heating demand, while photovoltaic energy generation showed only minor variations. These findings demonstrate that tailoring nZEB definitions to effectively balance energy supply and demand is essential.

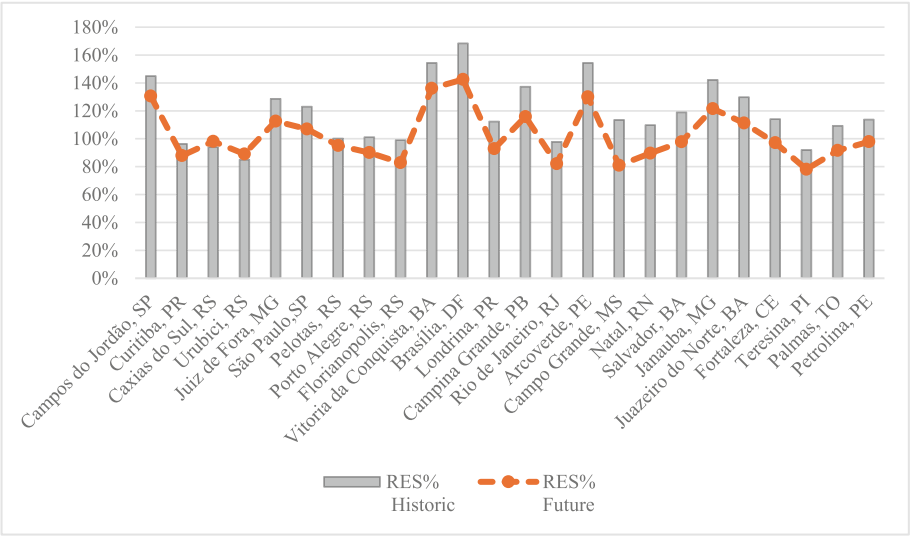


Fig. 2: Renewable Energy Supply historic and future scenario.

4 Conclusion

This research addressed the vulnerability of nZEB buildings to the impacts of climate change, particularly regarding the configuration of renewable energy systems required to achieve a net-zero energy balance. Especially in tropical and developing countries, the increase in energy demand is higher than the energy generated. Overall, the findings emphasize the importance of adaptive design strategies and continuous innovation to maintain the effectiveness and resilience of nZEBs under changing climate conditions.

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Preliminary Thermal Performance Assessment of the Monitored Building (ERDEM) Using PCM Integration

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Abstract. Monitored performance buildings are essential platforms for advancing sustainable and regenerative urban environments, as they provide the rigor and reliability needed to validate computational models and innovative design strategies. This study presents a preliminary thermal performance evaluation of the Monitored Building (ERDEM), located at the UFV Meteorological Station, focusing on the role of monitored spaces in fostering high-performance built environments. Over a 30-day monitoring campaign during autumn and winter (20° 45′ 14′S), two thermal zones were instrumented with sensors to capture heat flow and surface temperatures. The Control Zone (CZ) and Analysis Zone (AZ) offered comparable baselines prior to intervention, with Root Mean Square Error (RMSE) values for surface temperature as low as 0.10 °C, confirming the robustness of the monitored framework, using ASHRAE's Guideline 14. After the installation of the Phase Change Material (PCM), results indicated a reduction in the amplitude heat flow fluctuations, contributing to improved thermal comfort and enhanced energy efficiency. The PCM acted as a passive thermal regulator, delaying peak loads and smoothing temperature variations. Beyond the specific performance gains, this work underscores the broader importance of monitored environments as testbeds for sustainable materials and design solutions. In this context, ERDEM combines computational validation with energy-efficient technologies, such as PCMs, which play a pivotal role in reshaping the built environment.

Keywords: Phase change materials · Thermal performance · Monitoring · Sensors · Building energy efficiency

1 Introduction

According to the National Energy Balance [1], the building sector accounts for a significant portion of electricity consumption in Brazil: 27.5% in residential buildings and 16.9% in commercial buildings. Technical Note EPE 030/2018 from the Ministry of Mines and Energy further specifies that air conditioning systems are responsible for

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32% of the electricity consumed in residential buildings and 33% in non-residential buildings. These data indicate that the pursuit for thermal comfort represents a substantial share of the national energy matrix, primarily due to cooling demands. In this context, it is essential for buildings to achieve higher thermal and energy performance to reduce both environmental impacts and operating costs.

An effective strategy for understanding and improving the energy performance of buildings is the monitoring of their environmental properties. This process allows for an assessment of how building materials and systems respond to external variables - such as temperature, solar radiation and humidity- providing data-driven insights for targeted interventions. Previous studies indicate that, without this diagnostic stage, efficiency measures may be over or underestimated, compromising the effectiveness of the proposed solutions [2].

This paper presents a preliminary analysis of the thermal performance of a Monitored Performance Space (ERDEM) at the Federal University of Viçosa (latitude 20° 45′ 14′S, longitude 42° 52′ 53′O, altitude 698 m). The region is characterized by a humid subtropical climate (Cwa) according to the Köppen-Geiger classification [3]. This study compares two controlled environments within the building to verify their thermal-energy equivalence, thereby establishing a reliable baseline for future interventions. Based on this validation, the research aims to test passive strategies – such as the integration of Phase Change Materials (PCM) – that can contribute to reducing the energy consumption associated with space conditioning, fostering greater efficiency and sustainability in the construction sector.

2 Materials e Methods

The Monitored Performance Space (ERDEM) consists of a rectangular masonry structure built circa 1940, measuring 4.08 m × 7.08 m with a ceiling height of 2.95 m. The building features aluminium doors and windows, a precast concrete slab roof covered with ceramic tiles, and ceramic floor tiles. A detailed description of the construction components is provided in Table 1.

For monitoring and simulation purposes, the building was divided into four thermal zones, following the recommendations of the EnergyPlus Technical Manual [4] and the physical layout of the space. The core of the study focuses on two central zones: the Analysis Zone (AZ), with an area of 7.48 m^2, and the Control Zone (CZ), with 7.64 m^2. Additionally, to these, there are two peripheral zones located to the right of the AZ and the left of the CZ (bathroom), as illustrated in Fig. 1. This zoning strategy was adopted to enhance the monitoring of environmental conditions and to facilitate comparative performance experiments.

2.1 Sensor Identification

Environmental properties were monitored using two types of sensors: heat flow sensors (W/m^2) and thermoresistors (°C).

The sensor nomenclature followed a specific standard: those installed inside the Control Zone (CZ) and Analysis Zone (AZ) were classified as internal and assigned

Table 1. Thermal and physical properties of building elements.

Constructive element	Materials	Absorbance (α)	Thermal transmittance (W/m^2K)
Floor	Solid slab / Ceramic tile cladding		3.73
Wall 1	Mortar / Ceramic block / Mortar / Exterior paint	0.3	2.46
Wall 2	Ceramic tile cladding / Ceramic block / Mortar / Exterior paint	0.3	2.10
Wall 3	ACM / PCM / Ceramic Block	0.45	1.95
Coverage	Solid slab / Air chamber (>5.0 cm) / Ceramic tile	0.75	2.05

even numbers. Conversely, sensors positioned on surfaces facing away from the AZ and CZ were classified as external, even when located within adjacent thermal zones. Each pair consisting of a temperature sensor and a heat flux sensor shared the same identification number, distinguished only by the measurement type. The roof sensors were designated as internal, while floor sensors were defined as external.

The sensor layout is illustrated in Fig. 1. On the North walls, sensors were positioned between the floor and the windowsills (h = 1.30 m). On the remaining walls, the sensors were installed at the same height (h = 1.30 m).

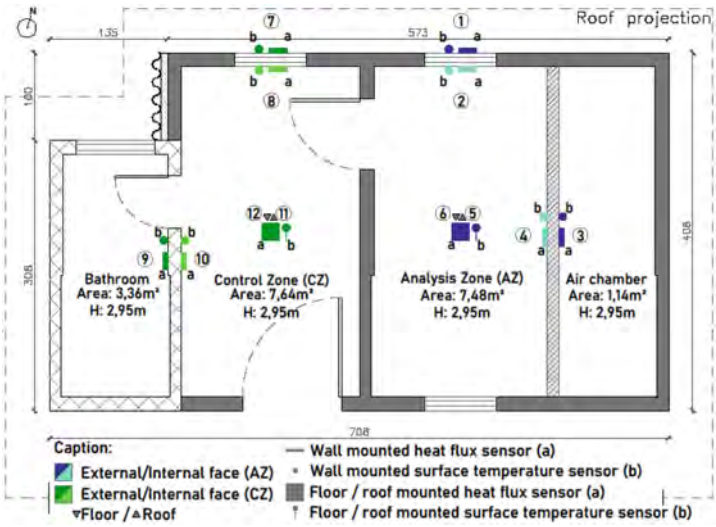


Fig. 1. Sensor Identification and Layout.

The sensors are color-coded to distinguish between the two primary thermal zones: blue and purple represent the Analysis Zone (AZ), while green and orange represent the Control Zone (CZ) sensors. To further differentiate the sensor positions, dark shades indicate sensors located on exterior surfaces and floors, whereas light shades designate sensors installed on interior surfaces and the roof.

2.2 Monitoring

All sensors were hardwired to a central computer, which integrated data from two distinct acquisition systems: one dedicated to heat flux sensors and the other to thermoresistors. Data were recorded at five-minute intervals ensuring high-resolution, [5] simultaneous measurements across all sensors.

The monitoring period spanned 30 days, covering the transition between autumn and winter. The experiment was divided into two distinct stages: Stage 1 (May 01–31): Boththe Analysis Zone (AZ) and the Control Zone (ZC) maintained equivalent thermal characteristics to stablish a baseline for comparison; Stage 2 (July 01–31): Phase Change Material (PCM) was installed in the AZ, enabling a comparative analysis of thermal performance between the modified environments and the CZ.

2.3 Data Collection

The data was collected weekly for preliminary analysis and cleaning. During the first stage, no anomalies, such as outliers or missing records, were identified. In the second stage, a 90-min data interruption occurred on July 24 (from 5:40 p.m. to 7:10 p.m.), which was subsequently corrected using linear interpolation to ensure dataset continuity.

Following initial verification, the data were systematised into tables to support the subsequent analyses. Due to the large volume of information, a representative time frame was defined for each experimental stage: Stage 1: From May 08 at 3:00 p.m. to May 18 at 2:55 p.m.; Stage 2: From July 18 at 3:00 p.m. to July 28 at 2:55 p.m.

Each selected period resulted in 2,880 records per sensor, providing a robust dataset for the construction of comparative graphs and optimised thermal analyses.

3 Comparative Analysis: Analysis Zone (AZ) vs. Control Zone (CZ)

The main objective of this analysis is to identify the differences and similarities between the two thermal zones based on monitored surface temperatures and heat flux. The characterisation of the envelope materials is essential for interpreting sensor data and calibrating the Energyplus numerical model (version 22.1). This calibration ensures that future interventions – such as the integration of PCM – can be evaluated with higher reliability.

The monitored walls share a similar core composition of ceramic brick and mortar. Externally, all surfaces are finished with mortar and white paint (Wall 1 – Table 1; Fig. 1). Internally, however, there are distinct variation: Bathroom walls feature ceramic tiles, while Control (CZ) and Analysis Zones (AZ) consist of painted mortar. Internal

variations distinctively define the AZ, featuring an exposed brick wall and a PCM-ACM layer integration.

This analysis is organised into two main sections: (1) Surface temperature analysis; and (2) Surface heat flux analysis. The next section looks at the data following the implementation of PCM.

3.1 Surface Temperatures

The ERDEM building is orientated close to the geographical North (Fig. 1), which minimises thermal disparities between the two study environments: the Analysis Zone (AZ) and the Control Zone (CZ). Figure 2 illustrates the surface temperature measurements obtained by thermoresistors on the internal faces of both zones.

Is the graphical data reveal a notable similarity in thermal behaviour between the zones, which is attributed to the solar orientation and construction uniformity. The external faces exhibit greater sensitive to climatic conditions, characterized by more pronounced heat gains and losses. In contrast, the internal surfaces maintain a reduced thermal amplitude. The characterisation of the thermal transmittance and resistance of the ceramic bricks is fundamental to understanding the thermal inertia of the building envelope.

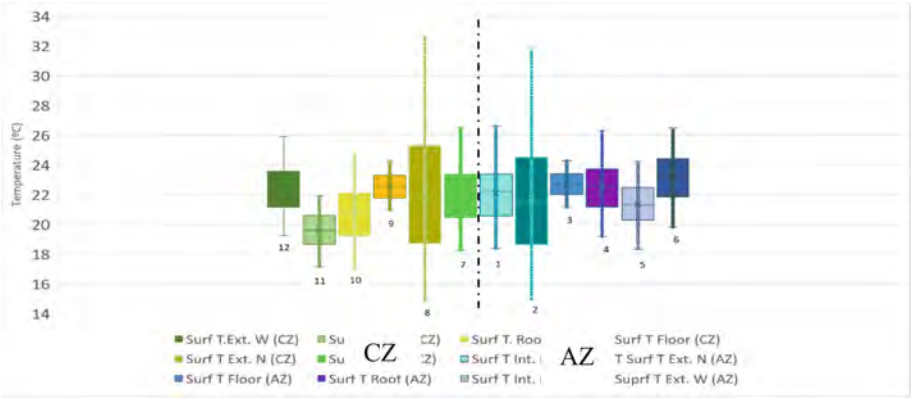


Fig. 2. Surface temperatures of the Control and Analysis zones.

The opposite walls, East (AZ) and West (CZ), exhibit the most significant differences. As previously noted, variations in internal coatings and the boundary conditions of adjacent areas – specifically the bathroom adjacent to CZ and the uncoated wall to the right of the A – directly influence these data. This, makes the monitoring process highly sensitive to these specific micro conditions.

According to Huerto-Cardenas [6], and following ASHRAE criteria [7], Root Mean Square Error (RMSE) values for surface temperatures of up to 2 °C are considered acceptable for model validation. Table 2 summarises the values obtained in this study, which fall within this threshold and confirm the robustness of the experimental model.

Table 2. RMSE values for surface temperatures.

AZ – CZ	RMSE (°C)	Sensors
North external surface temperature	0.60	1 and 7
North internal surface temperature	0.10	2 and 8
External surface temperature (east ZA and west ZC)	0.75	3 and 9
Internal surface temperature (east ZA and west ZC)	1.79	4 and 10
Surface temperature on the floor	1.75	5 and 11
Surface temperature on the roof	0.22	6 and 12

The fact that the RMSE indices remain within normative limits demonstrate a strong correlation between the two study environments. To further deepen the understanding of this thermal dynamic, a detailed heat flux analysis was performed.

3.2 Heat Flux Analysis

The heat flow data (Fig. 3) were analysed by designating positive values as heat gain and negative values as heat loss. On the internal surfaces – including floors, the roof and the opposite walls – the energy flux density ranged from -10 to $+25$ W/m^2.

The north walls, being more exposed to solar radiation, exhibited a net heat gain greater than the heat loss. This behaviour highlights the thermal storage capacity and the dynamic response of the building envelope.

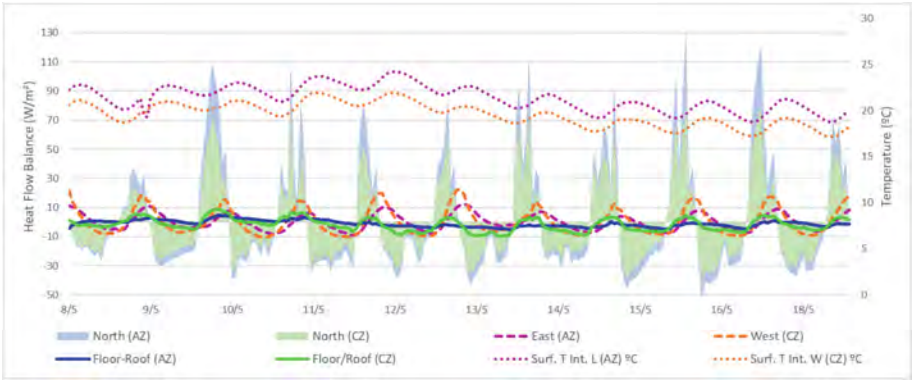


Fig. 3. Energy balance of heat flux in the Control (CZ) and Analysis (AZ) zones.

Although the roof of the CZ exhibits a slightly higher solar absorptacnce than that of the AZ, this is offset by an equivalent heat loss through the floor, establishing a thermal balance within the environment. During the monitored period, the cumulative energy balance (roof/floor) resulted in -267 W/m^2 in the AZ and -410 W/m^2 in the CZ.

A similar phenomenon is observed on the East and West walls. The energy gain recorded on the bathroom wall (adjacent to CZ) during the day is proportionally dissipated at night. The net energy balance on the East wall of the AZ, which absorbs less energy, was 42 W/m^2, compared to 120 W/m^2 on the West wall of the CZ.

4 Thermal Analysis with Phase Change Material (PCM)

The integration of Phase Change Material (PCM) within the Analysis Zone (AZ) promoted a convergence between the internal and external surface temperatures of the East wall. This integration effectively reduced the thermal amplitude, with a more pronounced impact on the minimum temperature values. Such thermal stabilisation is reflected in the maintenance of low RMSE values, as detailed in Table 3.

Table 3. Temperature RMSE for thermal zones before and after PCM installation.

AZ – CZ	RMSE (°C)	RMSE (°C) – PCM	Sensors
North external surface temperature	0.60	0.66	1 and 7
North internal surface temperature	0.10	0.16	2 and 8
External surface temperature (east/west)	0.75	0.30	3 and 9
Internal surface temperature (east/west)	1.79	1.77	4 and 10

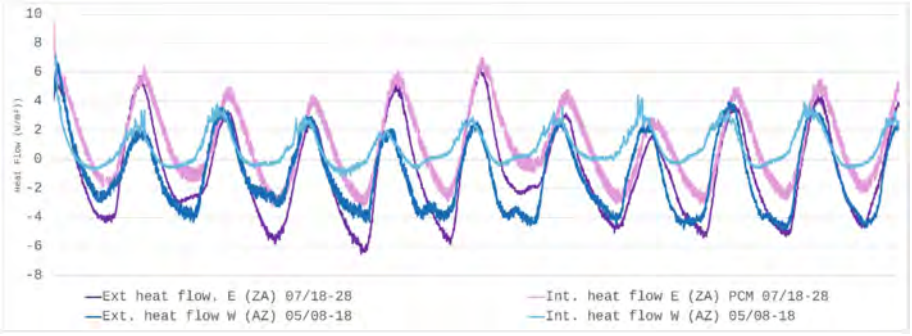


Fig. 4. Heat flux in the analysis zones before and after PCM implementation. The X-axis represents the 10-day monitoring period selected for each experimental stage, allowing for a direct comparison of the daily thermal cycles and the resulting time lag.

In addition to stabilising surface temperatures, the integration of PCM significantly altered the heat flux dynamics of the East wall in the Analysis Zone (AZ). The material attenuated the heat exchange between the internal and external faces (Fig. 4), which delayed and reduced the immediate transfer of heat to the building interior. While the Control Zone (CZ) showed marked heat losses through its external face during cold

days, the AZ maintained superior thermal stability. This performance is attributed to the latent heat storage capacity of PCM, which absorbs and releases energy during its phase transition, thereby dampening the impact of external climatic fluctuations (Fig. 4).

5 Conclusion

The results obtained through the experimental monitoring of the ERDEM building provided an accurate thermal characterisation of the study areas. The initial baseline analysis confirmed the thermophysical similarity between the Analysis Zone (AZ) and the Control Zone (CZ), with Root Mean Square Error (RMSE) values for surface temperatures consistently falling well below the 2.0 °C limit. Although localized variations were identified on the opposite walls (East and West) due to adjacent boundary conditions, the energy balance demonstrated that such discrepancies are compensated for by the internal dynamics of the environments, thereby validating the methodological rigour of the experimental platform.

The integration of Phase Change Material (PCM) in the AZ promoted a qualitative and quantitative shift in the thermal performance of the building envelope. Heat flux data revealed that the wall integrated with PCM operates under a thermal damping dynamic, attenuating the amplitudes of heat gain and loss compared to the CZ. Notably, the material provides substantial thermal lag, minimizing external temperature fluctuation impacts, particularly during colder days. While existing literature predominantly relies on numerical simulations, this work advances by providing empirical field data on PCM performance under real climate conditions.

In summary, this preliminary study reaffirms the effectiveness of passive systems with latent heat to enhance the thermal resilience of buildings. The ERDEM building has established itself as an essential laboratory for the validation of sustainable design strategies, providing robust data for the transition toward high-performance, low-energy built environments.

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A Data-Driven Framework Based on PMV Methodology for Holistic Evaluation of Smart Neighbourhood Regeneration Across Europe

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Abstract. This paper presents a comprehensive and adaptable evaluation framework capable of assessing energy and non-energy impacts in diverse urban contexts based on the Performance Measurement and Verification (PMV) methodology developed within the GINNGER project, used to evaluate energy-efficient and human-centred regeneration actions across six European neighbourhoods. The methodology builds on established PMV standards while introducing hybrid baseline estimation, real-time monitoring where available, and advanced forecasting and calibrated simulation models to improve accuracy in measuring energy efficiency, demand response performance, comfort conditions, and environmental outcomes in the built environment. It covers the full evaluation cycle, from ex-ante analysis to ex-post assessment, ensuring transparent and comparable performance measurement across different locations. A structured set of Key Performance Indicators (KPIs) complements the PMV approach, aligning monitoring activities and capturing impacts related to energy use, flexibility, comfort, mobility, environmental performance, and socio-economic value. Although the framework primarily focuses on technical aspects, it also incorporates user preferences regarding demand response events participation, comfort levels, supporting usability and acceptance while providing a scalable foundation for data-driven decision-making in smart neighbourhood regeneration.

Keywords: Performance Measurement and Verification · Demand Response · Energy Efficiency · Evaluation Framework · Smart Neighbourhood Regeneration

1 Introduction

In alignment with the European Commission's sustainable development agenda, municipalities and other local actors increasingly pursue the regeneration of derelict or inefficiently used neighbourhoods. The complexity of such initiatives, combining technological, operational and behavioural measures across multiple buildings and urban systems, requires robust evaluation frameworks capable of assessing multidimensional impacts [1, 2]. Structured evaluation supports consistent monitoring, comparison and validation of regeneration actions across diverse contexts [3].

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Measurement and Verification (M&V) methodologies provide standardized procedures for baseline definition, performance monitoring and savings estimation, enabling transparent and replicable assessment of energy efficiency interventions [4, 5]. Beyond savings verification, M&V frameworks also support continuous monitoring and informed energy management in sustainable energy projects [6]. While energy savings remain a primary objective of regeneration initiatives, their success also depends on broader non-energy impacts such as thermal comfort, environmental performance, economic benefits and user acceptance [7]. Incorporating non-energy indicators into evaluation frameworks enables a more holistic assessment of regeneration outcomes and supports the development of human-centred and socially inclusive smart neighbourhoods [8, 9].

The framework presented in this paper was developed within the Horizon Europe GINNGER project [10], which supports the regeneration of six European neighbourhoods through integrated technological and operational solutions, including energy efficiency retrofits, renewable energy systems, demand response mechanisms, smart energy management tools, user-centred digital solutions and co-creation actions. Given the diversity of interventions and pilot contexts, the proposed framework integrates hybrid baseline estimation, real-time monitoring, calibrated simulations and a structured KPI system to support consistent assessment of energy, comfort, environmental and socio-economic impacts in smart neighbourhood regeneration.

2 Framework Development Methodology

The GINNGER PMV framework was developed based on established M&V methodologies and standards, including the International Performance Measurement and Verification Protocol (IPMVP) [11], the Federal Energy Management Program (FEMP) guidelines [12], ASHRAE Guideline 14 [13], the Uniform Methods Project (UMP) [14], and demand response evaluation frameworks [15–17]. These methodologies were selected due to their widely adopted procedures for baseline definition, monitoring and impact estimation, as well as their applicability to both energy efficiency and demand response interventions implemented across the GINNGER pilots. Consequently, the framework adopts core principles from IPMVP and FEMP for baseline definition, monitoring and performance verification, while incorporating NAESB [15] recommendations for demand response assessment.

Building upon these principles, the framework provides a scalable and data-driven approach for evaluating regeneration actions across heterogeneous pilots. It integrates historical energy data, real-time monitoring where available, and forecasting or simulation models to support reliable baseline estimation and performance assessment. The framework supports systematic data acquisition, baseline modelling, monitoring and impact evaluation at building and neighbourhood levels. Monitoring results are analysed following PMV principles and expressed through standardized KPIs enabling consistent comparison and reporting across pilots.

3 KPI Selection

A concise set of tailored KPIs was developed to support the quantitative assessment of regeneration actions across the GINNGER pilots. The KPI framework complements the PMV methodology by translating measured and estimated performance data into standardized indicators capturing both energy and non-energy impacts across technical, environmental and social dimensions. KPI selection followed an iterative process involving project partners and pilot stakeholders to ensure alignment with project objectives, data availability and pilot-specific characteristics. The selected KPIs (Table 1) were designed to remain comparable across pilots despite differences in building typologies, climate conditions and monitoring capabilities, covering six categories: energy, environmental, comfort, economic, mobility and stakeholder engagement.

The KPIs are integrated into the PMV process by providing standardized metrics for baseline definition, monitoring and impact assessment. Baseline models establish reference values for KPI-related variables, while operational monitoring data enable the quantification of energy savings, demand flexibility and non-energy impacts through the corresponding indicators.

To support consistent KPI calculation and monitoring, each indicator is accompanied by a dedicated KPI card (minimised version in Fig. 1), available in [18], defining its description, calculation methodology, required input data, monitoring frequency, spatial granularity, baseline requirements and responsible stakeholders. These KPI cards support standardized and transparent KPI calculation across pilots while specifying the relevant monitoring data sources and digital solutions.

The GINNGER PMV framework follows a structured workflow; data collection, baseline estimation, performance monitoring, impact assessment, and reporting as shown in Fig. 2.

In practice, pilot sites implement the framework using local monitoring infrastructure, including building energy management systems (BEMS), smart meters, environmental sensors, and online questionnaires. These tools collect, process, and store operational data as well as end-user information needed for PMV analysis.

The process starts with gathering and preprocessing data from pilot sites: historical energy consumption, environmental conditions, system parameters, and real-time measurements where available. Data are validated and used to build baseline models that represent expected performance under reference conditions. Baselines employ a hybrid estimation approach, tailored to each pilot's data characteristics, variability, quality, and features, while aligning with established M&V standards.

During operation, monitoring systems capture actual performance data. PMV analysis compares these against baselines to quantify energy savings, demand flexibility, and non-energy impacts. Then, KPIs are calculated through standardized methodologies, and are aggregated either at building or neighbourhood levels, depending on the pilot context, for consistent cross-pilot evaluation.

The framework also incorporates user preference data via questionnaires to map behavioural patterns, enable adaptive responses, and boost acceptance of implemented actions. Finally, results feed into performance reports that validate impacts, enable comparisons, support decision-making, and allow ongoing refinement of baselines and procedures.

Table 1. Initial list of KPIs for the evaluation of the GINNGER project

KPI	Suggested Measurement Approach / (Main data sources)
Energy Consumption	Continuous monitoring and comparison between baseline and post-implementation performance using hourly data and calibrated simulations (Smart meters, energy usage profiles, occupancy data)
Final & Primary Energy Savings	Baseline vs. post-intervention comparison with hourly monitoring granularity (Energy consumption data, system efficiency values, primary energy factors)
Degree of Energetic Self-Supply by RES	Comparison of renewable energy production and consumption through real-time monitoring and daily aggregation (Renewable Energy Sources (RES) production data, consumption patterns)
Peak Demand Reduction	Baseline estimation and monitoring during Demand Reduction (DR) events with event-based reporting (Peak load measurements, DR event schedules, energy meters)
Reduced Energy Curtailment of RES and DER	Measurement of curtailed renewable generation before and during DR events (Real-time RES generation data, grid constraints)
GHG Emission Reduction	Lifecycle-based estimation linked to primary energy savings and fuel-specific emission factors (Energy usage data, fuel type, emission factors)
Decreased Emissions of Particulate Matter	Periodic monitoring of pollutant emissions and comparison with baseline conditions (Air quality sensors, PM pollutant measurements, energy source data)
Improved Thermal Comfort and User Well-Being	Combination of user surveys and environmental sensor measurements under baseline and operational conditions (Indoor temperature and humidity sensors, user feedback)
Life Cycle Costs	Annual lifecycle cost assessment considering installation costs, savings and operational expenditures (Financial audits, cost tracking, energy prices, energy savings)
Business Models Created	Qualitative assessment through annual reviews and stakeholder feedback (Business model descriptions, stakeholder input)

(*continued*)

Table 1. (*continued*)

KPI	Suggested Measurement Approach / (Main data sources)
Clean Mobility Utilization	Monitoring of EV charging activity and usage patterns of clean mobility solutions (EV charging data, mobility usage statistics)
Stakeholder Engagement	Monitoring participation in training, workshops, interviews and platform activities (Surveys, participation records)

KPI Title	**Degree of energetic self-supply by RES (%)**		**KPI ID**	**EN3**
KPI Description	The degree of energetic self-supply by RES is defined as the ratio of locally produced energy from renewable energy sources to the energy consumption over a period of time (e.g. month, year). Degree of energetic self-supply is separately determined for thermal (heating or cooling) energy and electricity, where both are available.			
Linked Pilot	P1 - P2 - P3 - P4	**Linked DS**	DS1 - DS2 - DS3	
	KPI Calculation			
Parameters to be measured	• renewable energy generation [MWh] • final energy consumption (thermal and electrical) [MWh]			
KPI Formula	%DE = (LPE/TE) x 100, DE = Degree of energy self-supply based on RES LPE = Locally produced energy [MWh/month] TE = Final energy consumption (monitored) [MWh/month]			
Data Type & Sources	Relevant data can be extracted from energy meters and/or simulations and/or databases of energy utilities/platforms.			
Spatial Granularity	Apartment Level	**X**	**Baseline Estimations**	Required
	Building Level	**X**		
	Pilot Level	**X**		
	Project Level			

Fig. 1. Indicative KPI card supporting calculation

4 Integration of User Preferences

In addition to technical monitoring and KPI-based assessment, the framework incorporates user preference data to capture behavioural factors influencing system operation and flexibility provision. Structured questionnaires collect information on comfort thresholds, willingness to participate in demand response (DR) events and communication preferences, ensuring that performance evaluation reflects both technical and behavioural aspects of energy efficiency and flexibility. The surveys capture acceptable comfort ranges, preferred DR timing and frequency, and feedback preferences, providing

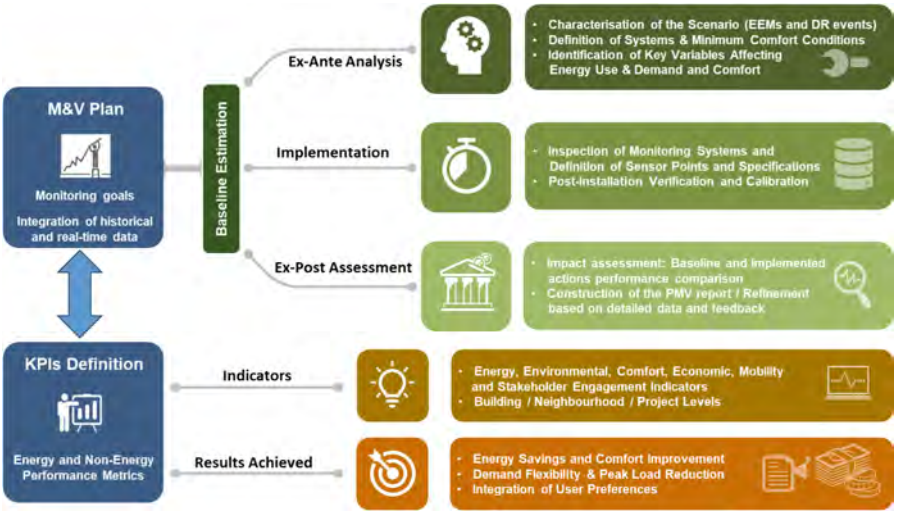


Fig. 2. Overview of the GINNGER PMV framework

insights into user acceptance and behavioural flexibility across pilots. More information on the questionnaire is available in [18], while detailed results will be reported in an upcoming project report.

Indicative survey results show favourable conditions for flexibility participation, with most users reporting moderate or high willingness to shift or reduce energy use, particularly when notified 24 to 48 h in advance via email or mobile applications. As shown in Fig. 3, most participants indicated willingness to engage in DR events weekly or even daily, while also reporting high adaptability in adjusting activities to accommodate energy management measures. Participants also expressed strong interest in digital platforms and maintained comfort preferences within typical indoor ranges. These findings support the operation of the project's digital marketplace for local energy sharing and demand-side services by improving the estimation and predictability of user-side flexibility and enhancing PMV validation through the integration of behavioural and technical factors.

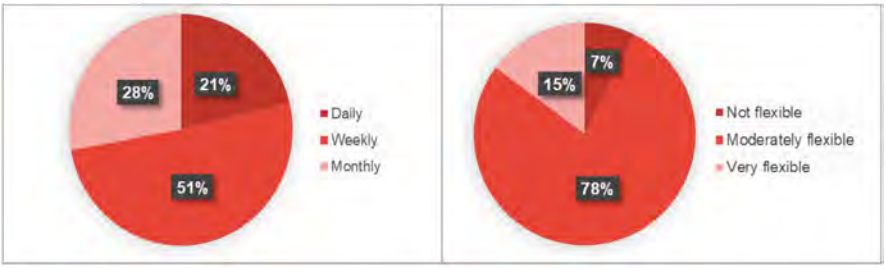


Fig. 3. Indicative DR participation preferences: Participation frequency (left), Self-reported flexibility for participation (right)

5 Conclusions

This paper presented a tailored PMV-based framework for the holistic evaluation of smart neighbourhood regeneration actions within the GINNGER project. The framework integrates baseline estimation, performance monitoring and impact assessment within a unified structure supported by a flexible and adaptable KPI set capturing both energy and non-energy impacts across different project and pilot contexts. By combining established PMV methodologies with hybrid baseline estimation, real-time monitoring, forecasting and simulation tools, the framework enables transparent and comparable assessment across diverse pilot contexts. Its scalable and human-oriented design is envisioned to support the evaluation of energy efficiency, demand flexibility, environmental performance, comfort and user engagement, while integrating behavioural data and digital flexibility management tools into the PMV process. The standardized KPI framework enhances transparency and reproducibility and supports evidence-based decision-making for future planning and investment strategies.

Beyond the GINNGER project, this framework holds potential for broader applications in urban planning and sustainable development. It can be adapted for evaluating district-level energy retrofits, smart city initiatives, or building portfolio assessments in public housing programs, where multi-dimensional KPIs are needed to balance technical performance with social outcomes. Municipalities and real estate developers could deploy it to benchmark neighbourhood-scale interventions against international sustainability standards, such as EU Green Deal targets, or national net-zero roadmaps. Additionally, it offers value in research contexts, like comparative studies of regenerative design in different climates, or in policymaking to quantify the co-benefits of green infrastructure investments.

Despite these strengths, the framework has notable limitations. Its accuracy relies heavily on the availability, quality, and granularity of monitoring data; incomplete datasets from sensors or user inputs can introduce biases in baseline estimates and forecasting models. The current KPI set, while flexible, may not fully capture site-specific cultural or socioeconomic factors influencing user behaviour. Moreover, full validation across all GINNGER pilots is ongoing, with preliminary results showing variability in performance metrics due to differing pilot scales and implementation maturity.

Acknowledgments. We would like to acknowledge the contribution of the project pilot leaders in the collection of data for the user preference survey, as well as the involvement of all project partners in the development of the framework.

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Materials and Innovation: Bio-based and Regenerative Materials, Advanced Composites, and Secondary Raw Materials through Industrial Symbiosis

Polyrock: Integrated Waste Polymerization for Sustainable Structural Building Materials and Other Products

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Abstract. The growing accumulation of plastic, domestic, agricultural, construction and demolition (C&D) waste presents a major environmental and economic challenge for both developed and developing nations. Traditional disposal methods such as landfill, incineration, and low-efficiency recycling are inadequate for achieving a closed materials loop in a circular economy. This research presents an integrated polymerization framework that converts mixed wastes into high-performance structural building materials and other products. The study focuses on combining thermal and microwaved integrated waste polymerization to produce composite building materials such as substitutes for structural dimension and engineered lumber, and numerous other structural and non-structural products such as bricks, boards, advanced fillers, etc. The main objective is to establish the scientific basis, process parameters, and performance validation necessary for a scalable waste-to-material pipeline. The project will integrate chemistry, materials science, and circular economy engineering to explore heterogeneous waste streams and how they can be stabilized, functionalized, and transformed into reliable, high quality structural construction materials and non-structural components, as well as possible byproducts of gases and other applications. The ultimate vision of this work is to contribute and support sustainable infrastructure technologies that align with worldwide net-zero missions and efforts to reduce waste and minimize harvesting of virgin raw materials.

Keywords: waste polymerization · microwave processing · waste streams · composite materials · circular economy · sustainability

1 Introduction

The global crisis of waste management contributed mostly by rapid urbanization and global population growth poses a huge environmental concern [1–3]. As the world population continues to grow, so does the rising accumulation of mixed plastics domestic, agricultural, construction and demolition (C&D) wastes, which present a real challenge to the realization of a circular economy [4, 5]. Current end-of-life treatments, including landfilling, incineration, and low-efficiency recycling fail to address the systemic need

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for a closed materials loop [6–8]. These traditional methods of recycling are often energy-intensive and result in "downcycling," where the reclaimed material possesses inferior properties compared to its virgin counterpart. To bridge this gap, a new conceptual model is required: the **Polyrock** Pipeline. Polyrock stands for polymeric or polymerized rock and was coined from polymerization of waste streams into composite, usable, hard or rock-like materials and components.

This model suggests that waste should not be viewed as a liability but as a feedstock for sophisticated use in chemical and structural engineering. A central contribution of the Polyrock pipeline study will be the formulation of an integrated polymerization framework conceived as a scalable waste-to-material conversion pipeline. The Polyrock architectural method and approach will involve use of thermal- microwave torrefaction of heterogenous waste materials. This approach is supported by recent research works on thermal microwave processing of waste materials. Studies shows that combining heat and microwave during waste processing supports the Polyrock system concept, which aims to convert waste into composite materials through an integrated process [9, 10]. This hybridization enables enhanced control over reaction kinetics and energy distribution, thereby facilitating the stabilization and functionalization of heterogeneous waste streams into usable materials.

The Polyrock framework is built to process mixed plastics and unsorted, nonhazardous domestic, agricultural, construction and demolition (C&D) waste. These sorts of feedstocks usually are considered unsuitable for conventional closed-loop recycling because of variable composition and contamination. Through the integration of thermal and microwave modalities, the process establishes well-defined physicochemical conditions for processing waste. These conditions promote the transformation of volatile and compositionally complex inputs into consistent, high-performance material outputs.

The resulting products will exhibit structural properties suitable for application as engineered building materials. Such materials hold the potential to serve as substitutes for dimension and engineered lumber, as well as structural and non-structural masonry and other components. The Polyrock processing method not only helps create a strong material composite but also allows for the simultaneous identification and recovery of secondary byproducts like gases, which can be used for other purposes.

Overall, by transforming heterogeneous waste into high-performance materials, we can minimize the harvesting of virgin raw materials and significantly reduce the carbon footprint of construction and other industries.

2 Conceptual Framework: The Integrated Polyrock Polymerization Pipeline

The core of the proposed framework is an integrated polymerization process that combines thermal and microwave processing techniques. The Integrated Polyrock Polymerization Pipeline is designed as a scalable system for converting waste into useful materials. The process combines conventional thermal processing with microwave-assisted torrefaction and polymerization to produce high performance structural products from

complex and unstable feedstocks. Drawing on principles from chemistry, materials science, and circular economy engineering, the framework defines the key reaction pathways, energy transfer dynamics, and operating conditions needed to stabilize and upgrade heterogeneous waste streams.

This combined processing approach addresses the variability and instability that typically limits the reuse of heterogenous and mixed waste materials. This process will enable conversion of such heterogenous waste materials into consistent, high-quality material. Such quality materials will then become useful in the production of building materials, additives and composites. The resulting materials from this work will have strong potential as alternatives to structural lumber, engineered wood products, and masonry units such as bricks and boards. At the same time, the process will allow for the capture and potential reuse of secondary byproducts, including gaseous streams, which can improve overall system efficiency.

More broadly, the Polyrock pipeline supports a closed-loop materials approach by reducing reliance on virgin resources and offering a practical alternative to landfilling and incineration. In this way, it contributes to ongoing efforts to meet sustainability goals, including those tied to global net-zero emissions targets.

2.1 Thermal and Microwave Synergy

Conventional thermal recycling and torrefaction processes often experience uneven heat distribution and uncontrolled degradation when treating heterogeneous polymer-rich waste streams. In this study, microwave-assisted processing is integrated with thermal treatment to provide volumetric heating and enhanced interaction with microwave-responsive phases within the waste matrix. Unlike conventional recycling approaches that primarily focus on material reduction or fuel recovery, the proposed Polyrock framework utilizes this thermal - microwave synergy to improve the stabilization of chemically diverse feedstocks. This approach assists in reducing the chemical volatility of mixed plastics and unsorted construction waste components, thereby promoting more uniform material transformation for improved composite product formation.

Functionalization: Microwave-assisted torrefaction improves and enhances the interfacial bonding between polymer resins and waste fillers, thereby producing a better and suitable composite for structural purpose and use.

2.2 Multidisciplinary Integration

The Polyrock pipeline is situated at the intersection of chemistry, materials science, and circular economy engineering:

Chemistry: Focuses on the molecular restructuring of waste polymers.
Materials Science: Governs the mechanical properties, durability, and performance validation of the resulting composites.
Circular Economy Engineering: Optimizes the process parameters for scalability and economic viability within a waste-to-material value chain.

3 Process Parameters and Material Stabilization

The transformation of waste into structural-grade material requires precise control over process parameters to ensure reliability. The conceptual Polyrock pipeline utilizes heterogeneous waste streams as primary inputs.

A critical step in this framework is the **stabilization** of these streams. Through controlled torrefaction of waste and polymerization, different elements of waste are bound into a cohesive matrix and then pulverized. This process not only manages the impurities common in mixed waste, but also allows for the functionalization of the material, tuning its chemical properties to meet specific structural requirements.

4 High-Performance Structural Applications

The primary output of Polyrock will constitute a suite of advanced composite materials capable of replacing traditional structural elements and also serve the purpose of other nonstructural needs.

4.1 Engineered Lumber and Dimension Substitutes

The framework will focus heavily on the production of substitutes for structural dimension and engineered lumber. These waste-derived composites are designed to mimic the load-bearing capacities of traditional timber and steel-reinforced products.

4.2 Diversified Building Components

The Polyrock mother product will demonstrate broad application potential across multiple sectors, with the capability of generating several derivative and potentially patentable products. Representative examples discussed in this study include applications in building materials, domestic products, fashion accessories, automobile components, industrial products, artistic applications, advanced fillers, and process byproducts. Additional examples and expanded classifications are provided in Appendix A.

5 Sustainability and Net-Zero Objectives

The ultimate vision of Polyrock is to contribute and support sustainable infrastructure technologies that align with worldwide net-zero missions.

5.1 Reduction of Virgin Material Extraction

By providing high-quality substitutes, the Polyrock pipeline reduces the environmental degradation associated with mining, timber harvesting, and the use of other virgin materials.

5.2 Waste Mitigation

The framework provides a scalable solution for waste streams that are currently unmanageable through traditional recycling.

5.3 Carbon Sequestration in Infrastructure:

By "locking" heterogenous mixed waste materials into long-term structural applications such as building materials, the pipeline serves as a form of carbon and material sequestration, preventing the release of greenhouse gases associated with incineration or decomposition.

6 Conclusion and Future Directions

Polyrock represents a sophisticated integration of waste management and structural engineering. By establishing a scientific basis for the microwave-integrated torrefaction and polymerization of unsorted, heterogeneous wastes, this research paves the way for a truly circular construction industry with genuine impact on diverse waste streams. Future work must focus on the refinement of scalable process parameters and the long-term performance validation of these composites under diverse environmental stressors, which is the mission of the continuing experimentations with Polyrock. Through this integrated framework, the vision of transforming waste into the backbone of modern infrastructure becomes a technical reality.

7 Current Stage of Experiment

This study explores an integrated pathway for transforming unsorted mixed waste into functional materials through thermochemical and materials engineering approaches. At its current stage, the work moves beyond conventional waste stabilization to demonstrate early-stage material valorization through composite fabrication.

7.1 Experimental Progress

Construction waste was torrefied under Nitrogen - low-oxygen inert conditions, producing a stable, carbon-rich material with improved brittleness and moisture resistance. Torrefied material was pulverized and it yielded a fine, homogeneous powder, facilitating its use as a functional filler. Pulverized material was then added at 10 wt.% to a bisphenol-based epoxy resin which was molded into a hexagonal composite tile, demonstrating effective integration of thermochemically treated waste into epoxy polymer matrix and resulting in a well-dispersed composite product (See Fig. 1).

7.2 Ongoing Work

The current work aims to move the material beyond proof-of-concept by thoroughly analyzing its physical and chemical properties and testing how well the composite performs mechanically and structurally. These findings will help refine both how the material is made and its composition.

7.3 Figures

Figures: (1A) Raw unsorted construction waste; (1B) torrefied material produced from the raw unsorted waste feedstock from figure 1A; (1C) pulverized torrefied feedstock produced made from figure 1B; and (1D) final composite tile produced from pulverized material from figure 1D in this study. The figures below illustrate progressive material transformation and evolution throughout the processing stages.



Fig. 1: Process flow illustrating the conversion of construction and demolition waste into a sustainable composite material: (1A) raw construction waste, (1B) torrefied construction waste, (1C) pulverized torrefied material, and (1D) composite specimen fabricated using BPA resin.

8 Assumptions

The assumptions of this work include that the unsorted waste feedstock is sufficiently representative of mixed construction and plastic waste streams and that microwave–thermal interaction effects remain consistent across varying material batches under controlled processing conditions.

9 Limitations

The limitations of the study include variability in waste composition, challenges in achieving uniform material behavior at larger scales, and the absence of long-term durability and field performance data for the developed composites. In addition, energy efficiency optimization and industrial-scale process validation remain outside the current ongoing experimental scope.

10 Delimitation

The delimitations of the study define the boundaries of the research to laboratory-scale processing of selected waste streams using the proposed Polyrock thermo–microwave framework. The study focuses primarily on material transformation and composite formation, and does not extend to full industrial deployment, lifecycle cost analysis, or certification-based structural validation.

Acknowledgement. I acknowledge Dr. Ben Ilozor, the Polyrock originator and the chair advisor for my Ph.D. program, who first envisioned heterogeneous polymerization of waste streams from construction, domestic, agricultural, industrial and plastic sources to produce vast, composite structural and non-structural products and byproducts. I would like to thank my colleague Matthew Finley for his support and contributions throughout this project. I am also grateful to ReMining Corporation for providing most of the resources that made this work possible. I appreciate Dean Rose, ReMining Corp. CEO for his leadership and continued support.

Appendix A

Expanded list of possible applicable products of "Polyrock" composite.

Building Products: Polyrock structural studs, columns, beams, joists, trusses, rafters, purlins, bricks, blocks, tiles, boards, sheathing, cladding, flooring, cabinets, cupboards, shelves, benches, fan hands, electric fixtures like can lights, lamp stands, switch pads, solid blinds, louvers, roof tiles, fascia boards, pipes, toilet bowls, bathtubs, sinks and vanities, baseboards, wainscot, cornices, doors, door knobs, window frames, trims, hardscape, landscape paving, fences, flower vases, decks, foundation footings, rafts and pads (substitution concrete), rainwater gutter, grilles, registers, ducts, screw nails, electric poles, conductor and wire insulation, etc.

Domestic Products: Drums, cans and utensils, tanks, storage, chairs, tables, bed frames and headboards, various domestic accessories, etc.

Fashion Products: Buttons, umbrella caps, combs, shoe soles, boxes, pen handles, helmets, hard book covers, various fashion accessories, etc.

Automobiles/vehicles: Body, dashboards, etc. – substitution metal and plastics.

Industrial Products: Palettes, containers of all sizes and different uses, computer CPU covers, keyboards, phones and phone covers, packaging, general electronic applications, fridge and freezer bodies, various industrial accessories, etc.

Arts Products: Frames, carving and painting boards, plaques, etc.:

Advanced Fillers: Utilizing subsequent Polyrock material to enhance the density and fire resistance of the polymer matrix.

Byproducts: The process is also designed to capture gases and other byproducts for potential industrial applications, further enhancing the efficiency of the materials loop.

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The Influence of Environmental Conditions on the Mechanical and Chemical Properties of Composite Materials for Use in Paving Stones

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Abstract. In recent years, the rapid accumulation of construction and demolition waste has emerged as a critical environmental challenge. At the same time, the global production of plastic waste continues to increase dramatically, intensifying the pressure on existing waste management systems and highlighting the urgent need for innovative, circular material solutions.

The aim of this research is to reuse construction waste (old brick) as fillers in composite paving stones. Recycled plastics (ABS) were also used as the matrix for the paving stones. This novel approach rethinks the conventional end-of-life pathways for both mineral and polymer waste streams, enabling their reduction in landfilling through repurposing and partial remanufacturing into functional construction materials.

As these 100% recycled composite materials are intended for outdoor exposure, tests were carried out to determine the impact of environmental conditions (including UV radiation, rainwater, acid rain, and sub-zero temperatures) on their morphology. The physical assessment showed no significant changes in sample mass after 2.5 months of exposure to sea water, acidic, and alkaline environments, with weight variations remaining below 0.2%, confirming the material's stability under aggressive conditions. The materials obtained, when the optimal parameters (composition and processing conditions) were selected, were characterised by high resistance to environmental conditions, even after prolonged exposure.

Keywords: Paving Stones · Composite · Construction Waste · Influence of Environmental Conditions

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1 Introduction

In today's rapidly evolving world, technological and industrial advancements have significantly impacted urban environments, necessitating innovative approaches to resource management. As societies become more aware of the environmental consequences of mass production and consumption, the need for sustainable solutions in urban systems has become more pressing. The challenge lies in optimizing resource utilization while minimizing waste generation and environmental degradation.

Material reuse and recycling have long been integral to human civilization, from remelting scrap metal and repulping paper to reclaiming construction materials and textiles. However, modern urban systems demand more advanced and efficient methods to handle increasing waste streams. The integration of digital technologies and circular economy principles is now essential for enhancing urban sustainability and resilience.

Plastics, widely used due to their affordability, durability, and versatility, have become a focal point of waste management challenges. Their production and disposal contribute to high energy consumption, carbon emissions, and landfill accumulation, underscoring the urgent need for innovative recycling and recovery strategies. According to Plastics Europe, global plastic production has risen steadily, from 370.7 million tons in 2018 to 413.8 million tons in 2023. In contrast the construction demolition wastes reach about 700 million tons in 2020 [1], reflecting the growing demand and the necessity for sustainable alternatives.

In response to these challenges, urban policies and regulatory frameworks have evolved to promote efficient waste management. A key initiative in this regard is the European Waste Framework Directive (WFD), first introduced in 1975 and later updated in 2008. This directive plays a crucial role in shaping urban sustainability strategies by encouraging waste prevention, resource efficiency, and the development of eco-friendly urban solutions. A cornerstone of the WFD is the European Waste Management Hierarchy, depicted in Fig. 1, which prioritizes sustainable waste handling practices, from prevention and reuse to recycling and recovery.

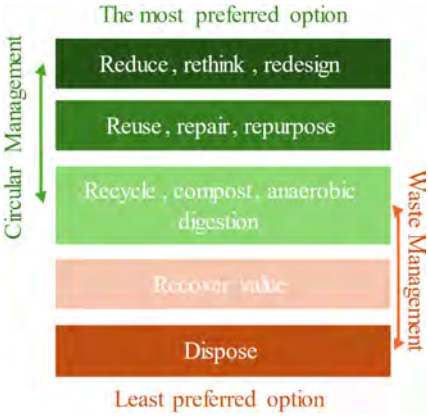


Fig. 1. Waste hierarchy model.

The implementation of these principles, supported by modern digital tools and technological advancements, is crucial for building low-carbon, efficient urban systems that enhance residents' quality of life while reducing environmental impact. It is this hierarchy that popularized the term "Reduce, Reuse, Recycle". The goal behind this hierarchy is to maximize the practical benefits of the product while minimizing the amount of waste and capture the ideas behind waste management and life cycle of each product [1].

Progressing further from the Waste Hierarchy, the model of Circular Economy began gaining popularity. According to the European Parliament definition, circular economy can be best described as "a model of production and consumption that involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended" [2]. By reusing materials that have been earlier categorized as waste, yet their condition still allows for repurposing or recycling into new elements. Within the range of the circular loops in the Circular Economy concept they can be divided as short, medium and long as presented in Fig. 2 [3]. Enhancing the management of plastic waste, particularly through advanced recycling strategies, is essential for reducing landfill accumulation and promoting sustainable urban systems. Despite regulatory efforts by the European Parliament, actual recycling rates remain low, with only 26.9% of plastic waste recycled in 2023. One of the major reasons might be the fact that still recycling of the materials meets plenty of barriers [4, 5]. This highlights the need for further innovation in waste recovery and material reuse.

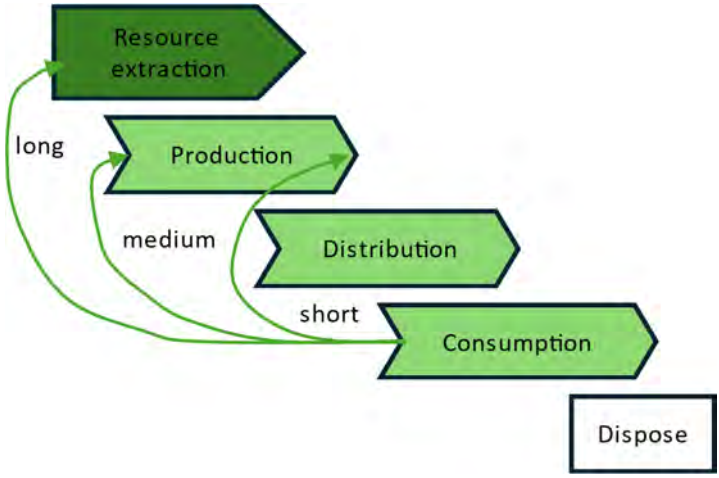


Fig. 2. Ilustration of loops in Circular Economy, based on [6].

To address this challenge, this study evaluates the impact of various environmental influences on an Acrylonitrile Butadiene Styrene (ABS)-based composite modified with up to 30% waste-derived aggregate. By integrating recycled materials, the research explores the feasibility of incorporating construction waste into polymer composites, contributing to circular economy principles and low-carbon urban development. This approach not only advances eco-friendly material design but also supports the development of sustainable urban infrastructure, where innovative solutions in material science play a key role in waste reduction, resource efficiency, and long-term durability. The findings contribute to the broader goal of creating resilient urban systems that align with modern sustainability demands while ensuring practical applicability in engineering and construction.

2 Experimental Part

The experimental part of this study includes the analysis of the performance of composite material made with ABS plastic as a matrix combined with waste brick aggregate acting as a filler.

2.1 Acrylonitrile Butadiene Styrene

Acrylonitrile Butadiene Styrene (ABS) is a popular thermoplastic polymer that is widely used due to its versatility. It is composed of 15% to 35% acrylonitrile, 5% to 30% butadiene and 40% to 60% styrene, and its nature allows for a lot of customization - different amounts of its constituents allow it to achieve many different properties. Important properties of ABS include its high impact toughness and resistance - the impact strength of ABS equals to 10–42 kJ/m2 for Izod Impact Test of a notched sample. Another important quality of ABS is its high stiffness - flexural modulus of ABS is equal to 1,6–2,4 GPa. The tensile strength of the ABS at yield is valued at 29,6–48 MPa. It is a lightweight material with a density of around 1.05 g/cm3. It also shows good resistance to abrasion. ABS is resistant to acid, alkalis as well as corrosion and biological degradation. It is easily moldable, either by extrusion or injection molding, allowing for use in a wide variety of applications. The disadvantages of ABS plastic include flammability - ABS is known to melt, burn and eventually combust when exposed to high temperatures. The melting point of ABS is around 200–240 °C. It is also sensitive to sunlight exposure, which may cause yellowing and brittleness of the material. The ABS used in the research comes from waste sources in the form of regrind which was then regranulated using a HAAKE PolyLab QC twin-screw extruder. Before processing, the material was dried at 80 °C for 5 h until the moisture was completely removed.

2.2 Waste Bricks Filler

The fine aggregate was produced from waste bricks obtained from the demolition of a building over 50 years old. The bricks were crushed to a particle size below 2 mm using a ball mill. The average density of the solid brick material was $\rho = 1.75$ g/cm^3. Due to an initial moisture content of approximately 4% and its negative effect on the selected polymer matrix, the aggregate was additionally dried at 100 °C for 24 h to ensure complete moisture removal.

2.3 ABS-Brick Composite Production

Composite materials based on an ABS matrix and a brick aggregate filler were produced using a Hakke Polylab QC drive and a Rheomix laboratory mixer. Previously prepared weights in appropriate volumetric proportions were placed in the mixer and then processed at 225 ° C for 5 min. The prepared masterbatches were then crushed using a Wanner blade mill. The crushed materials were then injected into the beam molds using a Proma pneumatic injection molding machine. The working pressure used to inject the composite materials into the mold was 5 bars. The final composition of the samples were 55 g of ABS and 45 g of waste brick per 100 g, which translates into 30% of the brick content by volume.

2.4 Resistance to Environmental Conditions Tests

To test the resistance of the samples to environmental conditions, measured and similar weights of samples were immersed in solutions simulating environmental conditions. Three types of solutions were used: sea water (Naturitas company, composition: chlorides (Cl) 23.2 g/l, sodium (NA) 9.8 g/l, magnesium (Mg) 0.359 g/l, sulfates (SO_4) 3.4 g/l, calcium (Ca) 0.409 g/l, potassium (K) 0.465 g/l, bicarbonates (CO3) 0.144 g/l, boron <2.4 mg/l, salt content 36.0 g/l, PH 7.0–8.0); acidic environment (1% sulphuric acid, pH = 1) and alkaline environment (2% sodium hydroxide, pH = 13). The samples were kept in solutions for 2.5 months at ambient temperature (approximately 20 °C) and with access to sunlight.

3 Results and Discussion

All samples were thoroughly dried (3 h at 50 °C), cooled, and weighed before immersion in solutions. After 1 and 2.5 months, they were removed from the solutions, rinsed five times in deionized water, dried, and weighed again. In each measurement series, three samples of similar weight were tested. The results were obtained for the sample with the greatest mass change (Table 1) show that the weight of the samples did not change as a result of exposure to solutions with specific properties (high salinity, low or high pH). This demonstrates the samples' high resistance to environmental conditions.

Table 1. Weights of samples before and after immersion in solutions

Solution	Sample	ABS
		30% brick
Sea water	Weight before	1.0877
	Weight after 1 month	1.0860
	Weight after 2.5 months	1.0886
Acidic environment	Weight before	2.7776
	Weight after 1 month	2.7750
	Weight after 2.5 months	2.7779
Alkaline environment	Weight before	1.0742
	Weight after 1 month	1.0730
	Weight after 2.5 months	1.0724

Imaging results (Fig. 3) obtained with an optical microscope (Leica) for a sample of ABS +30% brick before and after exposure to various environments showed that neither the sample surface nor its edge changed. There were no visible surface defects caused by leaching of polymer or aggregate from the sample interior. These observations are consistent with the results in Table 1.

UV-visible studies (Fig. 4) of the solutions in which the samples were stored were also performed. All spectra show a peak originating from the substances contained in the solution. In all cases, a slight change in the absorption height of the solutions is visible after the samples were stored in them. However, given that no significant new absorption peaks appear in the spectra, it can be concluded that the samples are not releasing significant amounts of substances from the polymers.

In summary, these results demonstrate that the composite cubes produced are physicochemical stable. Long-term storage of the materials in various solutions simulating environmental conditions did not result in leaching of the polymer material from the ABS matrix, but also, importantly, did not cause physical loosening of the mechanical structure or weakening of the matrix-filler bonds. Consequently, no mass loss or changes in the surface quality of the material were observed due to leaching of aggregate from the paving stones surface.

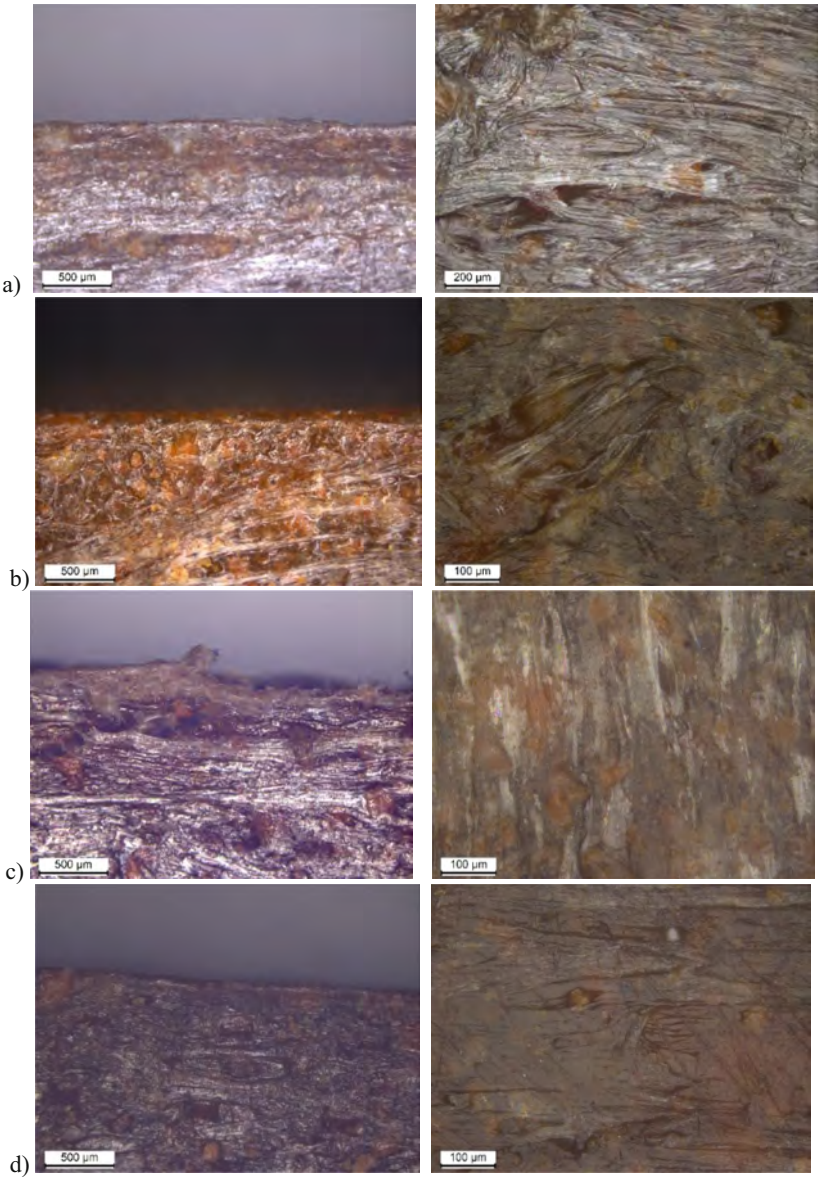


Fig. 3. Surface morphology of ABS +30% brick sample: a) before treatment; after 2,5 months in: b) sea water, c) acidic environment, d) alkaline environment.

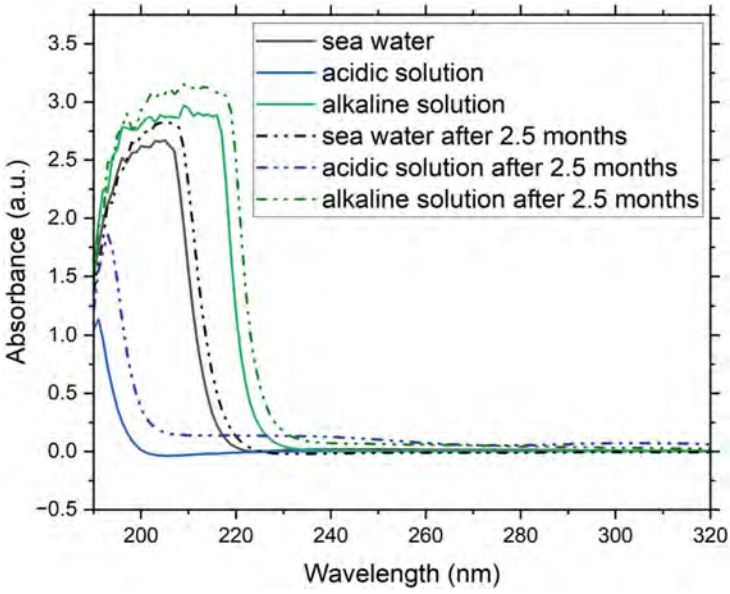


Fig. 4. UV-Vis spectra of solutions for composite resistance testing, reference solutions (continuous line) and solutions after 2.5 months with immersed samples (dashed line).

4 Conclusions

This study demonstrates that ABS-based composites modified with up to 30% waste-derived aggregate exhibit excellent resistance to diverse environmental conditions. Weight measurements over 2.5 months showed no significant changes after immersion in solutions of varying salinity and pH, indicating high material stability. Optical microscopy confirmed that neither the surface nor the edges of the samples were affected, with no visible defects or leaching of polymer or aggregate. UV-Vis analysis of the storage solutions showed only minor variations in absorption, suggesting minimal release of substances from the composites. These findings confirm the potential of incorporating construction waste into ABS composites to produce durable, eco-friendly materials suitable for sustainable urban infrastructure.

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The Effect of Sustainable, Biobased Epoxidized Soybean Oil/Pentaerythritol Ester Rosin Blends on Wood Protection

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Abstract. Utilizing natural bioactive compounds to enhance the service life of wood materials is a promising approach from both human health and environmental preservation perspectives. In recent years, significant efforts have been made to explore, develop, and refine new organic compounds for use in bio-composite production and wood preservation. In this study, pentaerythritol ester rosin (PEK) was synthesized and combined with epoxidized soybean oil (ESO) and Pinus sylvestris L. wood samples were impregnated with this solution prepared at different concentrations. Since PEK is prone to leaching from wood, it was blended with epoxidized vegetable oils to create a synergistic effect, ensuring stronger chemical bonding with the hydroxyl groups in wood. Various physical, chemical tests and analyses were conducted on the impregnated wood samples to evaluate their performance. The results showed that 20.0% PEK + ESO impregnation mixture was the most effective mixture for dimensional stability. This bio-based preservative system aims to extend the service life of woods while reducing reliance on petroleum-derived chemicals and heavy metals, thereby lowering the environmental footprint of wood protection.

Keywords: Sustainable · Pentaerythritol Ester Rosin · Epoxidized Soybean Oil · Wood Protection

1 Introduction

Wood is an extensively used engineering material characterized by a branched and interconnected structure composed primarily of cellulose, hemicelluloses, and lignin, along with minor organic extractives and inorganic components [1]. Wood is one of the oldest building materials and is widely used in furniture, architecture, and decorative applications due to its renewability, low density, favorable mechanical performance [2]. As a carbon-sequestering material, wood locks carbon dioxide out of the atmosphere throughout its service life. When used in long-lived building applications, this carbon storage benefit is further amplified. Treatments that extend the service life of wood therefore contribute directly to climate change mitigation. However, the lignocellulosic nature of wood can be a limitation in solid wood products, since its polar chemical groups negatively

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affect thermal stability, hygroscopicity, and biological resistance. Hydroxyl and methoxy groups increase the bulk hydrophilicity of wood, which raises the likelihood of drying defects such as cracks, bowing, and twisting [3]. To extend service life and improve performance, preservative treatment through impregnation is commonly applied [4]. However, most conventional preservatives are derived from non-renewable resources, making them incompatible with the principles of circular economy and sustainability [5].

For this reason, bioactive compounds derived from renewable natural products have gained increasing attention for wood protection. This is largely driven by growing concerns over the health and environmental hazards associated with heavy metal-containing wood preservatives [6]. Unlike synthetic preservatives such as chromated copper arsenate, bio-based systems derived from vegetable oils and rosin are biodegradable, come from renewable feedstocks, and have lower carbon footprints. In addition, bio-based preservation reduces the need for frequent replacement, which decreases timber harvesting demand and supports forest conservation. Treated wood with bio-based preservatives can be used in a wide range of building components, including structural elements such as beams, columns, and floor joists, as well as exterior cladding, decking, window frames, and garden structures. Improved dimensional stability and moisture resistance are especially important for outdoor and semi-exposed applications, where untreated wood is prone to biological degradation and mechanical failure.

Efforts to develop environmentally friendly wood preservatives have produced a large body of research on heat treatment, plant extracts, and bio-oils [7]. However, vegetable oils have several disadvantages that limit their practical use. These include the need for high oil loadings to achieve satisfactory performance, the tendency of oils to leach from wood over time, and the lack of inherent fungicidal activity. As a result, chemically modified oils have become an important strategy in wood protection. Among the various modification methods, epoxidation is one of the most widely used. Köse Demirel (2018) showed that epoxidized linseed oil and epoxidized soybean oil can effectively improve the water resistance and dimensional stability of Scots pine wood, even at low retention levels. Compared to untreated wood and wood treated with non-epoxidized oils, wood treated with epoxidized oils showed significantly lower water absorption and better anti-swelling performance [8]. Raw pine resin has also attracted attention as a wood treatment agent due to its low cost and renewable origin [9]. Pine resin consists of volatile terpenes (turpentine) and a non-volatile solid fraction known as rosin. Rosin is primarily composed of resin acids, which make up 90–95% of its composition, with the remainder consisting mainly of neutral compounds. These resin acids are diterpenic monocarboxylic acids, and the most abundant are abietane-type compounds [10, 11]. Their chemical behavior is strongly influenced by the position of conjugated double bonds and the presence of the carboxyl group. To improve stability and functional properties, rosin is commonly modified through esterification with alcohols or polyols such as ethylene glycol, glycerol, and pentaerythritol [12]. Due to its viscous nature, pentaerythritol ester of rosin (PEK) cannot chemically bond with the hydroxyl (-OH) groups in wood, which may lead to surface exudation after impregnation. Therefore, in this study, PEK was dissolved in epoxidized soybean oil (ESO) to promote more

effective interaction with the hydroxyl (-OH) groups within the porous structure of wood.

2 Materials and Methods

2.1 Materials

In this study, Scots pine (Pinus sylvestris L.) sapwood, Pinus pinaster rosin (natural rosin, R) and epoxidized soybean oil (ESO) were obtained from a local supplier in Türkiye. The chemicals employed in the esterification of rosin and treatment of wood included pentaerythritol (purity ≥ 99.9%; Sigma-Aldrich, St. Louis, MO, USA), (1,1-di-tert-butyl-4-hydroxyphenyl)methyl ethyl phosphonate (Irganox 1425; BASF; CAS No. 65140-91-2), and 4,4′-thiobis(2-tert-butyl-5-methylphenol) (TBM-6; 358.54 g/mol; Sigma-Aldrich), Acetic Acid (purity:≥99%; Sigma-Aldrich, St. Louis, MO, USA)

2.2 Methods

Esterification of Rosin with Pentaerythritol. The esterification reaction studies were conducted in accordance with the previous study [11]. The optimal synthesis conditions were determined to be a pentaerythritol/rosin molar ratio of 1:1, with TBM-6 and Irganox 1425 added at 1.0 wt. % and 0.5 wt. % relative to rosin, respectively.

Preparation of Impregnation Solution Mixtures. The formulations used for the impregnation treatment of Scots pine are given in Table 1. During impregnation solution preparation, the ESO was dissolved in pure acetic acid at a ratio of 70:30 (w/w). The purpose of blending PEK with ESO is to enhance the penetration of rosin into the wood structure.

Table 1. Impregnation solution mixtures

No	Impregnation solution mixtures
1	10.0% PEK + ESO
2	20.0% PEK + ESO
3	40.0% PEK + ESO

Wood Treatment Process. The impregnation solutions were introduced separately into Scots pine wood samples using a vacuum oven at 70 °C, under a vacuum pressure of 700 mmHg, for 3 h. Three rosin–ESO formulations 10% PEK + ESO, 20% PEK + ESO, and 40% PEK + ESO were used to improve the dimensional stability of the PCMs. After impregnation, the ESO-treated samples were cured at 80 °C for two weeks. Acetic acid vapor was used during curing to promote ESO polymerization. To achieve this, acetic acid was placed at the bottom of a sealed container, and the samples were positioned above the liquid level. This ensured that the samples were exposed only to the vapor phase, with no direct contact with the liquid.

Weigh Percentage Gain (%). Weight percentage gain (WPG) was calculated using the dry mass before and after the treatment Eq. (1),

$$\mathrm{WPG}(\%) = ((\mathrm{W}_2 - \mathrm{W}_1)/\mathrm{W}_1) \times 100 \quad (1)$$

Where W_2, weight of the impregnated and dried sample and W_1, initial weight of the conditioned sample prior to impregnation.

Water Absorption and Tangential Swelling Test. Water absorption (WA) and tangential swelling (TS) of the wood samples were calculated according to AWPA E4-03. For each variation, 10 replicates with dimensions of 20 × 20 × 10 mm (Tangential × Radial × Longitudinal) were prepared. Prior to testing, the samples were dried in an oven at 70 °C for 24 h. Treated and untreated samples were then placed into beakers filled with deionized water. The water was replaced with fresh deionized water after 0.5, 1, 2, 4, 6, 24, and 48 h, and subsequently at 48-h intervals for 2 weeks. The mass and dimensions of the samples were recorded after each replacement. All experiments were conducted at room temperature. WA and TS were calculated using Eq. (2) and (3) after each water replacement.

$$\mathrm{WA}(\%) = ((\mathrm{W}_2 - \mathrm{W}_1)/\mathrm{W}_1) \times 100 \quad (2)$$

$$\mathrm{TS}(\%) = ((\mathrm{TS}_2 - \mathrm{TS}_1)/\mathrm{TS}_1) \times 100 \quad (3)$$

Where W_1 and W_2 are the mass of the wood specimens before and after test; TS_2 is the tangential dimension at any given time during water-soaked condition; TS_1 is the initial tangential dimensions of the wood samples.

Fourier Transform Infrared Spectra (FTIR). The FTIR spectra of the treated wood samples were obtained using a PerkinElmer Frontier spectrometer equipped with an attenuated total reflectance (ATR) accessory. Spectral data were collected in the range of 4000–500 cm^{-1} at a resolution of 4 cm^{-1}.

Scanning Electron Microscope (SEM): The internal microstructural characteristics of treated (10%, 20%, and 40% PEK + ESO) and untreated (control) wood samples were examined on the radial plane using a scanning electron microscope (SEM; Zeiss Supra 40). Before SEM examination, all specimens were sputter-coated with a thin gold layer to enhance electrical conductivity. Surface micrographs were recorded at 300× magnification.

3 Results and Discussion

3.1 Weight Percentage Gain (%) Results

The WPG of treated samples were shown in Table 2. WPG indicates the amount of treatment solution retained in the wood after impregnation and curing. Higher WPG values generally reflect greater chemical uptake and more effective wood modification.

The results show that lower concentration formulations may provide better impregnation efficiency, whereas higher concentrations may limit penetration due to increased viscosity. This finding is consistent with previous studies, which reported that solution viscosity strongly affects chemical uptake and distribution in the wood structure [1, 8].

Table 2. Weight percentage gain of treated samples

Variation	WPG (%)
10.0 %PEK + ESO	83.5 (10.22)
20.0 %PEK + ESO	70.03 (7.99)
40.0 %PEK + ESO	68.92 (7.26)

3.2 Water Absorption and Tangential Swelling Results

Water absorption (A) and tangential swelling (B) results for treated and untreated wood samples are presented in Fig. 1. The letters in the parenthesis refer to Dun-can homogeneity groups based on $p < 0.001$. Water absorption increased with immersion time for all samples. A rapid increase was observed during the first soaking period, particularly between 0.5 and 24 h, followed by a more gradual increase up to 336 h.

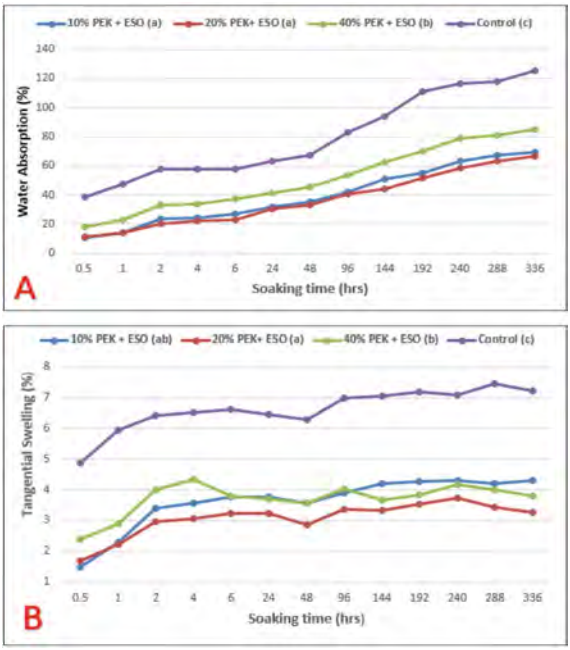


Fig. 1. Water absorption (A) and Tangential swelling of treated and untreated samples (B) and their Duncan homogeneity groups based on the repeated measures of ANOVA $p < 0.001$.

This behavior is typical for wood-based materials and is primarily attributed to the rapid filling of cell lumens and capillary spaces in the early stages, followed by slower water diffusion into the cell wall. Similar water uptake behavior has also been reported for oil-treated wood, where the initial rapid absorption was followed by a slower increase during prolonged soaking periods [13]. The untreated control samples

exhibited the highest water absorption throughout the entire soaking period, increasing from approximately 38–40% at 0.5 h to about 125–130% after 336 h. This is attributed to the hygroscopic nature of wood, its open capillary structure, and the abundance of hydroxyl groups in the cell wall components. In contrast, all PEK + ESO treated samples showed lower water absorption than the control, confirming that the treatment improved water resistance. This result is consistent with [13], who reported that wood treated with epoxidized plant oils showed significantly lower water absorption than untreated control samples after long-term water exposure. The 10% and 20% PEK + ESO formulations performed best, reaching water absorption values of approximately 65–70% after 336 h. This reduction is likely due to partial filling of the cell lumens and structural modification of the wood. In addition, the epoxidized soybean oil (ESO) component may have increased wood hydrophobicity, thereby limiting water penetration. It was also indicated that epoxidized oils can be distributed within wood lumens and ray cells, which may contribute to improved hydrophobic performance [13]. Similarly, tangential swelling increased with immersion time for all samples. The increase was more pronounced during the initial soaking period and became more gradual thereafter. All PEK + ESO treated samples exhibited lower tangential swelling than the control, indicating improved dimensional stability [13]. The statistical analysis showed that treatment variations significantly affected both water absorption and tangential swelling. According to Duncan's multiple range test at the 95% confidence level ($\alpha = 0.05$), all treated samples exhibited significantly lower water absorption than the control. The lowest water absorption values were observed at 20%PEK + ESO (39.27%) and 10%PEK + ESO (40.01%), which belonged to the same homogeneous subset, indicating no statistically significant difference between them. The 40%PEK + ESO group showed a higher water absorption value (50.79%) and formed a separate subset, while the control group had the highest value (80.07%) and was statistically different from all treated groups. Similarly, tangential swelling was significantly reduced by the treatments compared with the control. The lowest swelling value was obtained for 20%PEK + ESO (3.06%), followed by 10%PEK + ESO (3.50%) and 40%PEK + ESO (3.80%). The 10%PEK + ESO group overlapped with the other treated groups, indicating that the differences among treated samples were not statistically pronounced. However, the control group showed the highest tangential swelling value (6.67%) and formed a distinct subset, confirming its significantly lower dimensional stability compared with the treated samples.

3.3 FT-IR Results

The FT-IR spectra of the untreated and treated wood samples are presented in Fig. 2. Clear differences were observed between the control and treated samples. The bands at 2912–2926 cm^{-1} and 2840–2862 cm^{-1} were associated with aliphatic C–H stretching vibrations, while the peaks at 1723–1747 cm^{-1} were assigned to ester carbonyl (C=O)

groups. The higher intensity of these bands in the treated samples indicates the successful incorporation of the rosin–ESO formulations into the wood structure. Changes in the fingerprint region also suggest interactions between the treatment of chemicals and the lignocellulosic components of wood. Overall, the FT-IR results show that the treatment modified the chemical structure of the wood.

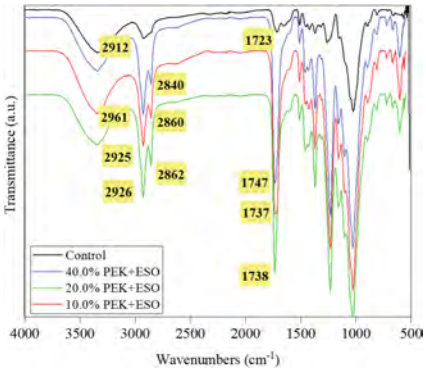


Fig. 2. FT-IR spectra of untreated and treated wood

3.4 SEM Results

SEM micrographs are shown in Fig. 3. It is shown that untreated wood preserved its natural porous structure, while treated samples exhibited deposits on the cell walls and partial lumen filling. Among the treated groups, the 20.0% PEK + ESO sample showed a more homogeneous distribution and better surface coverage, indicating effective penetration and balanced retention within the wood structure. These findings suggest that the 20.0% PEK + ESO formulation provided favorable impregnation performance.

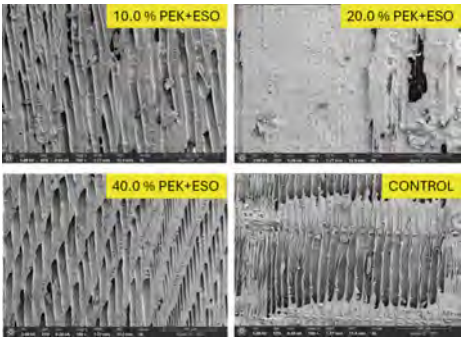


Fig. 3. SEM micrograms spectra of untreated and treated wood

4 Conclusions

The results indicate that PEK + ESO treatment significantly improves the dimensional stability and water resistance of the wood samples. Among the tested formulations, moderate concentrations (10–20%) appear to provide more effective water-repellent performance than higher concentrations, likely due to better penetration and more

uniform modification of the wood structure. In particular, the 20% PEK + ESO formulation achieved the most effective dimensional stabilization, suggesting that moderate concentrations offer the best balance between penetration depth and chemical modification.

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Enhanced Production of Mycelium Biocomposites from Hemp Substrates for Sustainable Buildings

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Abstract. Mycelium-based biocomposites (MBCs) are promising regenerative materials for sustainable construction, combining fungal growth with agricultural residues to create low-carbon alternatives to fossil-based products. This study presents an optimised production approach for hemp-based MBCs using three *Trametes versicolor* strains and one *Ganoderma resinaceum* strain cultivated on fractionated hemp stalks. A novel inoculation method, based on drying and milling colonised grains into a powdered inoculum, was applied to accelerate colonisation, improve growth uniformity, and increase batch consistency. After incubation and thermal inactivation, the composites were evaluated for density, surface wettability, and thermal conductivity, with extruded polystyrene (EPS) used as the reference material. The results showed that the mycelium composites were substantially denser than EPS, while still achieving comparable thermal conductivity, with selected formulations matching or outperforming EPS. Surface wettability was strongly strain-dependent: composites produced with *T. versicolor* 9 and *G. resinaceum* 2 showed hydrophobic behaviour comparable to EPS, whereas *T. versicolor* 11 and 12 were more wettable. Coarser hemp fractions generally improved structural integrity and, in some cases, thermal performance. Due to space limitations, not all experimental results are presented here; however, the selected findings demonstrate the strong potential of mycelium–hemp composites as bio-based, biodegradable, and climate-responsive materials for non-structural building applications.

Keywords: Mycelium Biocomposites · Regenerative Materials · Climate-Responsive Design · Circular Economy · Fungal Biotechnology

1 Introduction

The construction industry faces pressure to reduce its environmental footprint, responsible for 39% of global carbon emissions and consumes many non-renewable resources [1]. Traditional building materials such as concrete, steel, and petroleum-based insulation

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contribute significantly to embodied energy, greenhouse gas emissions, and waste. In 2015, the U.S. construction sector generated 565.8 million metric tonnes of CO_2, while plastic production for construction adds 9.5 to 10.5 million metric tonnes of CO_2 annually [2]. Researchers and industry stakeholders are exploring bio-based alternatives that sequester carbon, use agricultural waste, and biodegrade at end-of-life. Mycelium-based biocomposites (MBCs) are promising, combining fungal networks and lignocellulosic substrates to create lightweight, insulating, and biodegradable building materials [3–5]. Hemp (*Cannabis sativa*) is ideal for mycelium cultivation due to its rapid growth, high cellulose content, low environmental impact, and availability as an agricultural by-product [3, 4]. Hemp shives, the woody core left after fibre extraction, offer an excellent carbon source and structural matrix for fungal colonisation. The combination of mycelium and hemp substrate forms a biocomposite, with fungal hyphae transforming agricultural waste into functional building materials [5, 6].

This report presents a comprehensive analysis of current research on mycelium-hemp biocomposites for sustainable construction. It examines production methods, sustainability metrics, material properties, building applications, and future development pathways. The analysis draws on recent peer-reviewed literature to assess the technical feasibility, environmental benefits, and commercial potential of these innovative materials in meeting the urgent need for sustainable building solutions.

1.1 Mycelium Biology and Material Formation

Mycelium is the vegetative part of fungi, consisting of a network of thread-like hyphae that grow through and bind organic substrates. When supplied with suitable lignocellulosic feedstock, moisture, and environmental conditions, fungal mycelium secretes enzymes that break down complex carbohydrates while simultaneously forming a dense, interconnected network [7]. This biological process transforms loose substrate particles into a cohesive composite material through natural adhesion and mechanical interlocking [8].

The material properties of mycelium biocomposites depend critically on the fungal species selected, substrate composition, and growth conditions. Basidiomycete fungi, particularly white-rot species such as *Pleurotus ostreatus*, *Ganoderma lucidum*, and *Trametes versicolor*, are commonly used due to their efficient lignocellulose degradation and robust hyphal networks [9, 10]. These fungi produce chitin-rich cell walls that provide structural integrity and contribute to the material's mechanical properties [11].

1.2 Hemp as a Substrate Material

Hemp cultivation offers several environmental advantages as a substrate source for mycelium composites. The plant grows rapidly, requires minimal pesticides and fertilisers, and can be cultivated on marginal land unsuitable for food crops [12]. Hemp shives, the primary by-product of hemp fibre processing, contain approximately 40–48% cellulose, 18–24% hemicellulose, and 21–24% lignin, an ideal composition for fungal colonisation [13].

The porous structure and high surface area of hemp shives facilitate efficient mycelial penetration and binding, while the material's natural antimicrobial properties help prevent contamination during cultivation [14]. Additionally, hemp's carbon sequestration during growth contributes to the overall carbon-negative profile of hemp-mycelium composites [15].

1.3 Composite Formation Mechanisms

The formation of mycelium-hemp biocomposites involves several interconnected mechanisms. First, fungal hyphae physically penetrate and interweave through the substrate particles, creating a three-dimensional network that mechanically binds the material [16]. Second, mycelium secretes extracellular polymeric substances and hydrophobins, which act as biological adhesives, chemically bonding the substrate particles [17]. Third, the fungus's consumption of substrate nutrients modifies the material's chemical composition and microstructure, influencing the final properties [17].

The drying and heat treatment processes that terminate fungal growth also significantly affect material properties. Controlled drying produces a rigid, lightweight structure as the hydrated hyphal network collapses and consolidates [18]. Heat treatment above 70 °C inactivates the fungus, preventing further growth and potentially improving water resistance and dimensional stability [19, 20].

2 Materials and Methods

2.1 Sample Preparation

Three *Trametes versicolor* strains and one *Ganoderma resinaceum* strain from the culture collection of the Department of Wood Science and Technology, Biotechnical Faculty, University of Ljubljana, were used to produce mycelium biocomposites. Extruded polystyrene (EPS) was used as the reference material for comparison of physical and thermal properties. Fungal cultures were first transferred to Petri dishes, after which actively growing mycelium was inoculated onto sterilised, hydrated cereal grains. The grains were incubated until fully colonised, then dried and milled into a fine inoculation powder, which was used to inoculate the final lignocellulosic substrate (hemp stalks). Conventional methods of inoculation include liquid and grain-based techniques. While the powdered inoculum aims to improve distribution, further comparative data are needed to confirm its advantages. The powdered inoculum approach was explored as an alternative to conventional methods.

The hemp stalks were fractionated to obtain substrate particles of defined length, then sieved to control particle size distribution. Fractionation used a Retsch mill to generate specific size classes. Two substrate particle size categories were used: fine and coarse. Before inoculation, all selected hemp fractions were hydrated to an appropriate moisture level and sterilised in an autoclave at 121 °C and 150 kPa for 2 h.

Following sterile inoculation with the powdered mycelium culture, the substrates were incubated until fully colonised. The fully colonised composites were then thermally inactivated and conditioned. Each strain–substrate combination was used to produce five

replicate composite panels with nominal target dimensions of 120 × 120 mm and a thickness of 25 mm. After inactivation, specimens were allowed to equilibrate before further analysis. Statistical analysis was conducted using mean values, standard deviations, and replicate measurements to ensure experimental reliability. Mass and dimensional measurements (length, width, thickness) were recorded to enable calculation of density before testing physical and thermal properties.

2.2 Contact Angle Measurements

The contact angle (CA) of distilled water was measured using the sessile drop method with a Theta Optical Tensiometer. Measurements were conducted on the surfaces of the mycelium-based composites and EPS. Water droplets of 4 μL were deposited on the specimen surface. Images were acquired over 60 s at a rate of 15 frames per second (FPS). The start of the recording was defined as the first image showing a self-supporting drop on the substrate. CAs were determined by computer-aided image analysis using OneAttension, applying the Young–Laplace fitting mode to the recorded droplet profiles. For each material, three measurements were performed on five specimens at 23 °C.

2.3 Thermal Conductivity Measurements

Thermal conductivity (λ) was determined under steady-state conditions using a guarded hot plate in accordance with EN 12667:2001 [21]. Before testing, specimens were conditioned under standard climatic conditions until equilibrium was reached. For each material group, 4–5 replicate specimens were analysed at a mean temperature of 25.5 °C with an imposed temperature gradient of 13 °C. Once steady-state heat flow was established, thermal resistance was recorded, and thermal conductivity was calculated as in Eq. (1), where d is the mean specimen thickness in mm, and R is the measured thermal resistance in m^2K/W.

$$\lambda = \frac{d}{R} \tag{1}$$

3 Results and Discussion

3.1 Density of Mycelium Composites and EPS

The mycelium biocomposites were consistently denser than the EPS reference. EPS showed low densities of 22–25 kg/m^3, whereas the mycelium composites ranged from approximately 101 to 149 kg/m^3. For *G. resinaceum* 2, fine fractions reached 127–138 kg/m^3 and coarse fractions 129–149 kg/m^3. For *T. versicolor* 12, densities ranged from 120–133 kg/m^3 (fine) and 117–128 kg/m^3 (coarse), showing substantial overlap. *T. versicolor* 11 composites had densities of 108–116 kg/m^3 for fine fractions and 123–131 kg/m^3 for coarse fractions, while *T. versicolor* 9 ranged from 101–116 kg/m^3 (fine) to 119–129 kg/m^3 (coarse). Overall, coarse fractions generally produced slightly denser composites than fine fractions, particularly for *T. versicolor* 9, *T. versicolor* 11, and *G.*

resinaceum 2. Combined with the thermal conductivity results, these findings suggest that it is possible to tailor mycelium composites within a relatively narrow density window, while adjusting particle size and strain to balance mechanical robustness and insulating performance.

3.2 Contact Angle Measurements

The contact angle (CA) measurements revealed clear strain-dependent differences in the surface wettability of the mycelium composites, while substrate particle size had only a minor effect (Fig. 1a and b). Among the coarse-fraction composites, the highest initial CAs were recorded for *G. resinaceum* 2 and *T. versicolor* 9, with mean values of approximately 108.5° and 111.3°, respectively, indicating strongly hydrophobic surfaces. In contrast, *T. versicolor* 11 and especially *T. versicolor* 12 exhibited lower initial CAs, around 80.6° and 66.7°, reflecting more hydrophilic behaviour. A similar trend was observed for fine-fraction composites: *T. versicolor* 9 showed the highest initial CA (117.6°), followed by *G. resinaceum* 2 (107.7°) and *T. versicolor* 11 (104.2°), whereas *T. versicolor* 12 again showed the lowest value (67.1°). The EPS reference remained highly hydrophobic, with initial CAs of 104.7°. All materials showed a decrease in CA over the 60 s measurement period, indicating progressive wetting. Overall, the results indicate that fungal strain is the main factor governing surface wettability, whereas particle size plays a secondary role. Composites produced with *T. versicolor* 9 and *G. resinaceum* 2 showed hydrophobic behaviour comparable to EPS and may therefore be more suitable for applications requiring water repellence. By contrast, the greater wettability of *T. versicolor* 11 and 12 may be advantageous where improved adhesion, coating compatibility, or moisture interaction is desired.

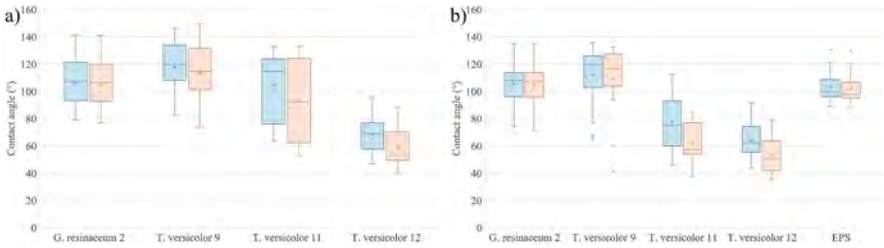


Fig. 1. Contact angle (CA) measurements of distilled water on mycelium composites and EPS reference samples produced with a) fine and b) coarse particles. Blue boxes represent the CA measured after 1 s, and orange boxes represent the CA measured after 60 s.

3.3 Thermal Conductivity of Mycelium Composites and EPS

Thermal conductivity (λ) was measured for 38 mycelium composites and 5 EPS reference samples (Fig. 2). The mycelium composites showed λ values from 36.62 to 52.81 mW/m·K, with a mean of 42.46 mW/m·K, while EPS averaged 42.94 mW/m·K over a wider range of 36.25–62.64 mW/m·K due to one high outlier. Overall, the

mycelium composites displayed insulation performance comparable to EPS, with lower variability. Hemp particle size had a modest effect. Coarse fractions showed a slightly lower mean λ (41.99 mW/m·K) than fine fractions (42.94 mW/m·K), suggesting somewhat better insulation with larger particles. Strain-related differences were also observed. *T. versicolor* 11 produced stable values around 42 mW/m·K, indicating consistent EPS-like performance. Fine *T. versicolor* 12 showed some of the lowest values (36.6–40.6 mW/m·K), whereas coarse *T. versicolor* 12 had a broader range up to 52.8 mW/m·K. Coarse *T. versicolor* 9 also performed well, with values of 37.8–39.7 mW/m·K, while fine *T. versicolor* 9 and fine *G. resinaceum* 2 tended to be higher (45–47 mW/m·K). These results show that both fungal strain and substrate fraction influence thermal conductivity, and that selected combinations, particularly coarse *T. versicolor* 9 and fine *T. versicolor* 12, can match or outperform EPS.

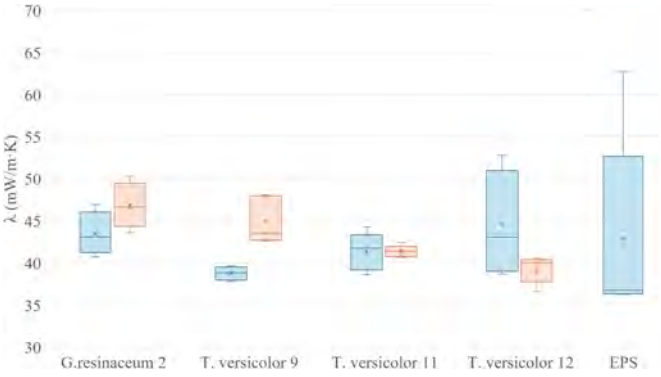


Fig. 2. Distribution of thermal conductivity (λ) for mycelium biocomposites and EPS. The graph shows λ values for *G. lucidum* and each *T. versicolor* strain, separated by substrate particle size (coarse in blue, fine in orange).

4 Conclusions

This study showed that hemp-based mycelium biocomposites can match EPS in certain properties, while being bio-based and biodegradable. The method, using powdered inoculum from dried and milled grains, enabled uniform colonisation and reproducible composite formation across fungal strains and substrate fractions. The results confirmed that all mycelium composites were denser than EPS, with values ranging from 101 to 149 kg/m^3, compared with 22–25 kg/m^3 for EPS. Despite higher density, the composites exhibited comparable thermal conductivity, with a mean value of 42.46 mW/m·K versus 42.94 mW/m·K for EPS. Surface wettability was strongly strain-dependent, whereas substrate fraction had only a minor effect. Composites produced with *T. versicolor* 9 and *G. resinaceum* 2 exhibited hydrophobic behaviour comparable to EPS, while *T. versicolor* 11 and 12 were more wettable, which may be advantageous where adhesion or coating compatibility is required. Findings indicate fungal strain selection and substrate

fractionation effectively tailor density, wettability, and thermal performance. The study confirms mycelium–hemp composites' potential for non-structural, climate-responsive building applications, especially in thermal insulation and panel systems, with comparable performance to conventional materials. However, limitations like mechanical strength, durability, and moisture resistance need further investigation. Testing under real conditions will focus on durability and long-term evolution of properties such as density and thermal conductivity, to understand potential performance degradation over time.

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Regenerative Design Through Invasive Plant Species Biomass Valorisation: Turning Ecological Threats into Bio-Based Materials in Southern Europe

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Abstract. The spread of invasive plant species is accelerating biodiversity loss, with significant ecologic and economic costs. Their control can represent an opportunity for regenerative and circular material innovation using a biomass that is not valued. This work focuses on the potential of invasive plant species biomass as a bio-based material for regenerative design applications in Southern Europe, aligning with the increasing demand for building decarbonization strategies. The study aims to assess whether the abundant and often problematic biomass of invasive plants can be transformed into construction materials, thus contributing simultaneously to management control action and material innovation. The methodology is based on a structured literature review, combining an assessment of invasive species distribution to identify high-impact species and a mapping of current research trends to evaluate which species and material applications have been most studied. The results highlight a set of promising species, such as common reed (*Arundo Donax*) and Pampas grass (*Cortaderia Selloana*), with favourable physical or chemical properties suitable for bio-composites, fibres, panels, and other regenerative material applications. The analysis also identifies knowledge gaps, particularly in areas such as scalability, long-term performance, and integration into existing material value chains. The review concludes that valorising invasive plant biomass may support regional management efforts while offering alternative sources for bio-based materials, aligning with regenerative design principles that seek to restore ecosystems rather than merely minimise harm. This approach offers an ecological and material opportunity for Southern Europe, where invasive species proliferation and the demand for climate-positive materials are simultaneously increasing.

Keywords: Biomass Valorisation · Invasive Plant Species · Regenerative Design · Bio-based Materials

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1 Introduction

The construction sector remains one of the largest contributors to global greenhouse gas emissions and resource consumption [1, 2], intensifying the urgency for material innovation aligned with climate neutrality goals. Despite the impact, the lack of mitigation policies on CO_2 emissions is a current issue in the building sector [2]. The IPCC's sixth report [3] proposes adopting low-carbon materials and nature-based solutions to reduce the long-term embodied carbon in buildings. In the European context, the European Green Deal [4] aims to decarbonise the EU's building stock by 2050, positioning Europe to lead as the first climate-neutral continent, while the Energy Performance of Buildings Directive (EPBD) recast of 2022 [5] stipulates the life cycle assessment of the Global Warming Potential (GWP) for new buildings starting in 2030. However, despite progress in exploring agricultural residues and forestry by-products, biomass from invasive plant species remains underestimated.

The economic impact of managing invasive species is substantial. In Europe, the costs are estimated to have reached €116.61 billion between 1960 and 2020, with 60% of this amount attributed to damage across multiple sectors [6]

Additionally, as global temperatures continue to rise, the species may occupy an even larger area, where climatic conditions favour aggressive growth and resilience. According to Tarabon et al. [7], for some species, models indicate northward and eastward expansion under future climates despite already occupying substantial regions along the western and Mediterranean French coasts. Management strategies typically rely on mechanical removal, controlled burning, or landfill disposal, practices that incur public costs while generating limited environmental return [8]. This approach frames invasive biomass as waste rather than as a potential resource.

However, studies on rapidly growing species have highlighted the material potential of plants, particularly due to their high cellulose content, fibrous structure, and widespread availability in Mediterranean territories [9]. Yet, research remains fragmented, often focusing on isolated material tests without integrating biomass availability, ecological management strategies, and construction value chains.

This study extends circular and bio-based construction research toward regenerative approaches. Regenerative design approaches seek to restore ecological systems and generate positive environmental impact. In this sense, the removal and valorisation of invasive plant biomass present a dual opportunity: mitigating biodiversity loss while supplying renewable raw materials for the built environment.

This study addresses the gap between the distribution and impact of invasive plant species in Southern Europe and their potential to be used in construction through a structured literature review and comparative mapping analysis. The research aims to evaluate the feasibility of transforming invasive plant biomass into bio-based construction materials within the Southern European context. Specifically, it seeks to answer the following questions:

- Which are the most problematic invasive plant species in Southern Europe that could have potential biomass valorisation?
- What types of material systems and products have been explored in the literature?

By synthesising ecological distribution data with material research trends, the paper proposes a transdisciplinary perspective that links biodiversity management to regenerative construction material innovation. The approach emphasises the use of already problematic and abundant species as a transitional resource.

A regenerative design perspective, drawn from systems-based theories of Bill Reed [10], emphasises the restoration and improvement of ecological systems rather than merely reducing damage. In this context, the removal and utilisation of invasive biomass is a strategy for waste management and a contribution to ecosystem recovery and biodiversity support.

This approach reflects a shift from linear environmental management to integrated socio-ecological systems thinking. Ecological challenges become inputs to industrial processes, linking construction activity with ecosystem restoration. Despite practical, technical, and regulatory constraints, this framework supports evaluating invasive plant biomass as a strategic resource for regenerative construction.

2 Methodology

The study dataset comprises 104 alien plant species occurring in Mediterranean countries, namely Portugal, Spain, France, Italy, and Greece. Species were compiled from two complementary sources: the European inventory of alien species provided by the DAISIE database [11] and the regulatory list of invasive alien species of Union concern under Regulation (EU) No 1143/2014 [12], maintained by the European Commission and updated in 2025.

Species from the DAISIE database were included when they had documented occurrences in Mediterranean ecosystems or were widely reported as invasive or naturalised within southern European countries. In addition, all plant taxa listed in the EU Union List were incorporated into the dataset, even when their occurrence frequency in Mediterranean regions was limited.

The inclusion of these regulated species reflects a precautionary approach, as they are officially recognised as ecological or socio-economic threats within the European Union and may expand their distribution, undergoing environmental change.

By integrating observational data from DAISIE with policy-driven species from the EU regulatory framework, the resulting dataset captures both currently widespread invasive plants and species considered high-risk for future establishment. This combined approach provides a comprehensive representation of invasive flora relevant to Mediterranean ecosystems while ensuring alignment with European management priorities.

Occurrence records were retrieved from the Global Biodiversity Information Facility (GBIF) [13], a global biodiversity repository containing georeferenced species observations.

As a second stage, this study adopts a structured literature review to assess the potential of the listed invasive plant biomass for construction applications in Southern Europe.

The review was conducted using the scientific databases Scopus and Web of Science, selected for their broad coverage of peer-reviewed research in environmental sciences, materials engineering, and construction. Studies were selected based on the focus

on invasive plant species present in Southern Europe and the exploration of material applications within the built environment.

The search strategy was organised around combined keyword clusters to capture interdisciplinary intersections. The following keyword combination was used: "sustainable building" OR "biobased construction material" OR "construction material" OR "sustainable building material" OR "Biomass valorisation", followed by the boolean operator "AND" and the names of the selected species.

Exclusion criteria were applied to language, as only publications in English were selected, publication type (only journal article and conference proceedings) and the year of publication, only the last 5 years' publications, meaning 2025, 2024, 2023, 2022, 2021. The five-year time frame was made to focus on the current state of research in biomass valorisation, considering the evolution of processing technologies and performance assessment in this field.

3 Results

To identify the most widespread and well-documented taxa for further analysis, two quantitative filtering criteria were applied. First, species were required to have confirmed occurrences in all five Mediterranean countries considered in the study. This criterion reduced the dataset from 104 to 50 species. Second, species were required to exceed a threshold of 10,000 occurrence records across these countries, ensuring sufficient data availability and focusing on the most widely established invaders. Applying this threshold resulted in a final subset of 31 species that satisfied both criteria.

Surprisingly, only three of these 31 species are currently included in the list of invasive alien species of Union concern. This result highlights a notable discrepancy between the species that are most widespread and frequently recorded across Mediterranean Europe and those formally prioritised within the European regulatory framework. However, many of the selected species are present in national lists, for example, 15 of the 31 species are listed in the Portuguese national list of invasive species [14].

The analyses in this study focus on the 31 species (Table 1), representing the most widespread and well-documented invasive plants within the study region.

Selected invasive plant species originate predominantly from the Americas and Asia, reflecting historical trade and horticultural exchange. The predominance of ornamental introductions highlights horticulture as a major driver of plant invasions, as many species introduced for landscaping subsequently escaped cultivation and established in disturbed habitats. Among the 31 species analysed, 19 originated from the Americas, 8 from Asia, 3 from Africa, and 2 from Western Europe. Only seven species were introduced after 1900, indicating that the majority are long-established components of Mediterranean alien floras.

About the use of these species as materials for product development in construction sector, the results identified 95 publications related to the selected species and the keywords selection. However, when the search was refined to include studies directly associated with material-based innovation, only 8 papers were found (Fig. 1). This indicates that research exploring the valorisation of these invasive species as materials or construction-related resources remains very limited.

Table 1. Selected invasive species widespread in southern Europe.

Species	Occurrences in southern Europe	Species	Occurrences in southern Europe
Ailanthus altissima[1,2]	62420	*Lepidium draba*	38709
Amaranthus retroflexus[2]	45615	*Lonicera japonica*[2]	12294
Ambrosia artemisiifolia	63416	*Mahonia aquifolium*	13118
Species	Occurrences in southern Europe	Species	Occurrences in southern Europe
Arundo donax[2]	64201	*Nicotiana glauca*[2]	12902
Bidens frondosa[2]	38796	*Oenothera biennis*	17372
Broussonetia papyrifera[1]	19550	*Opuntia ficus-indica*	13150
Carpobrotus edulis[2]	20525	*Opuntia stricta*	19013
Cortaderia selloana[2]	24833	*Oxalis pes-caprae*[2]	47632
Cyperus eragrostis	28225	*Paspalum dilatatum*	21390
Datura stramonium[2]	52090	*Paspalum distichum*	16620
Erigeron annuus	66304	*Phytolacca americana*[2]	50023
Erigeron bonariensis	20738	*Robinia pseudoacacia*[2]	189205
Erigeron canadensis	156727	*Senecio inaequidens*[2]	56414
Eucalyptus camaldulensis	55934	*Setaria pumila*	31428
Heracleum mantegazzianum[1,2]	18108	*Ulex europaeus*[2]	88419
		Xanthium orientale	23813

[1]Species that appear in the list of invasive alien species of the European Union concern [12].
[2]Species that appear in the Portuguese national list of invasive species [14].

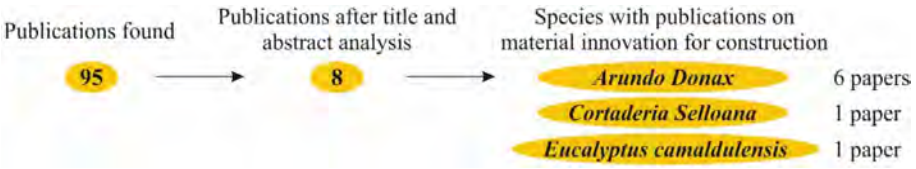


Fig. 1. Publications' overview

Among the analysed species, *Arundo donax* showed the highest research activity, with 40 publications, six of which were directly related to material-based innovation.

These studies mainly focus on the use of biomass derived from *Arundo donax* for material production and industrial applications. The studies have explored the species in several material systems, including bio-composite blocks [15], thermal insulation or cladding solutions [16], and characterisation of the raw material [17, 18].

The second most represented species was *Robinia pseudoacacia*, with 11 publications, although none of them was directly related to material-based innovation in the context considered in this review. Most of the identified studies focused instead on biomass valorisation and energy-related applications.

Other species showed significantly lower research activity. Cortaderia Selloana was mentioned in 2 publications, but just one study related to the characterisation of the biomass for construction purposes [19]. *Eucalyptus camaldulensis* had 7 publications, with one study that relates the species to other materials [20], while *Broussonetia papyrifera* (6 publications) was mainly associated with bioenergy research rather than material applications. Similarly, *Amaranthus retroflexus* and *Lonicera japonica* presented five publications each, but none addressed material-based innovation.

Several species in the list showed very limited or no presence in the literature during the analysed period, including *Heracleum mantegazzianum*, *Lepidium draba*, *Mahonia aquifolium*, *Setaria pumila*, and *Xanthium orientale*. This suggests that they remain largely unexplored in the context of biomass valorisation.

Furthermore, even when publications were identified, the majority of them addressed environmental management, phytoremediation, biochar production, biomass pyrolysis, or species control strategies, rather than the development of sustainable products or construction materials.

For example, *Ailanthus altissima* studies focused primarily on phytoremediation, biochar, or bioenergy, *Ambrosia artemisiifolia* research mainly addressed species dispersal and land management, *Nicotiana glauca* was investigated mainly for phytostabilisation of contaminated soils, *Ulex europaeus* studies focused on biomass pyrolysis or chemical production.

4 Discussion and Conclusion

Overall, the results highlight a clear research gap between the ecological management of invasive species and their valorisation as raw materials for sustainable product development or construction applications. Despite the growing interest in bio-based materials and circular economy approaches, only a small fraction of the identified literature explores these invasive species as potential sources of innovative materials. Invasive species removal is primarily implemented to restore ecosystem balance and protect biodiversity. However, the biomass generated through these control actions represents a largely underestimated resource.

By redirecting biomass flows, it can support regenerative construction practices and present contributions to construction decarbonisation strategies, as fast-growing plant species may substitute carbon-intensive materials.

However, several limitations must be considered, including the risk of encouraging invasive species cultivation, regulatory restrictions on their use and transport, and uncertainties related to market acceptance and industrial scalability.

Key findings from this study can be summarised as follows:

- Only a small number of invasive plant species demonstrate documented potential for material applications in the construction sector.
- Existing research is largely concentrated on biomass valorisation for energy, biochar, or environmental remediation rather than construction materials.
- Significant knowledge gaps remain regarding fibre properties, processing techniques, and the integration of invasive biomass into construction material systems.

Future research should focus on experiments to evaluate the technical feasibility of invasive biomass in construction applications. Additionally, policy integration is essential to ensure that invasive species management strategies can safely incorporate biomass valorisation pathways without compromising ecological protection objectives.

These research directions may support the development of regenerative material strategies that transform ecological management challenges into opportunities for sustainable construction innovation.

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Testing Campaign on Durability of Natural Fibre Textiles in Concrete Members

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Abstract. In recent years, the importance of non-metallic reinforcement made of natural fibres has been gaining relevance. Previous investigations have suggested that impregnation is a critical aspect for the mechanical and long-term performance of concrete components reinforced with natural fibres.This study aims to understand the influence of distinct impregnation methods and materials, namely mechanical rolling and vacuum impregnation, on the me-chanical performance, bonding behaviour, and durability of natural fibre yarns intended for textile-reinforced concrete.To this, reinforcements made of sisal, hemp, and flax yarns, as well as selected hybrid configurations, were systematically examined. The tensile properties were determined prior to textile production in accordance with a standardised fibre strand testing procedure. Multiple specimens were tested to capture the material variability and to evaluate the resulting variation in stiffness and strength.The results indicate that strength, stiffness, and scatter varied substantially de-pending on material and processing method. Vacuum impregnation increased the modulus of elasticity from 1.8 up to 2.2 times compared to the rolling im-pregnation with notable differences across yarn types and combinations. Addi-tionally, the results suggest that appropriate pairing of yarn material and im-pregnation technique can significantly enhance load-bearing capacity and con-trol deformability.This study provides a systematic comparison of impregnation techniques for various natural fibre yarns, showing how these methods interact and influence mechanical performance. The comparison supports the selection and combina-tion of suitable yarns and impregnation techniques for textile reinforcements in structural concrete. It also identifies opportunities for further optimizing natural fibre reinforcement systems to achieve durable and structurally efficient con-crete components.

Keywords: Natural fibre textiles · Textile-reinforced concrete · Durability

1 Introduction

Over the last few years, the potential of non-metallic reinforcement systems in the construction sector has been emerging (e.g., [1, 2]). In particular, rod-shaped and textile reinforcements based on carbon or glass fibres have become established as effective alternatives to conventional steel reinforcement due to their high tensile strength, low self-weight and pronounced resistance to corrosion (e.g., [1–3]). The utilisation of these

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materials enables the design of more slender structural elements compared to conventional steel-reinforced elements, thereby, expanding architectural design possibilities [1–3]. Despite their favourable mechanical properties, synthetic high-performance fibres have been discussed in the context of sustainability [4–6]. The energy-intensive production of these materials is typically associated with a comparatively high CO_2 footprint, conflicting with resource-efficient construction ambitions for the sector [4–7].

To overcome the environmental drawbacks of synthetic reinforcements, plant-based natural fibres have been raising attention within the construction materials research community [5, 6, 8, 9]. Natural fibres such as flax, hemp or jute represent potentially ecological alternatives, as they are derived from renewable resources and exhibit a lower emissions balance compared with that of synthetic fibres [5–7, 9]. In addition, they are locally available in many regions [5, 6, 8]. Numerous studies demonstrate that natural fibres present satisfactory mechanical properties in both polymeric and cementitious matrices for application as a reinforcement [5, 6, 8–12]. However, previous investigations have been focusing on the utilisation of short, discontinuously embedded fibre systems, which primarily contribute to crack control (e.g., [8, 9, 11, 13]).

Despite such research developments, the durability of impregnated natural fibre textiles in concrete applications remains ambiguous particularly related to their long-term behaviour in the highly alkaline environment of concrete [4, 8, 11, 14]. It is known that plant-based fibres are sensitive to alkaline attack, as components such as lignin, hemicelluloses and pectins are degraded at high pH values, which may lead to structural deterioration [11, 16]. For a suitable application as a reinforcement material, a deeper understanding of the underlying degradation mechanisms is, therefore, required.

This aim of this study was twofold: Firstly, to propose an impregnation solution to improve the durability of natural fibres fabrics embedded in concrete and, secondly, to identify a suitable impregnation method.

To this, plant-based yarns are processed into woven or knitted fabrics and, subsequently, impregnated with epoxy resin. The resin impregnation enhances the internal bonding of the yarns, simultaneously acting as a protective layer against moisture, alkaline exposure and mechanical abrasion [4, 12, 14]. The properties of the impregnation significantly influence the resulting stiffness, tensile strength and the ecological assessment of the composite material [4, 10, 12, 14, 15].

2 Tested Material

In this investigation, a commercial powerRibs textile fabric (Bcomp) was utilized. The textile fabric is made of flax fibres and has a 0°/90° grid architecture with a mesh opening of 28 mm. The yarn has fineness of 3000 tex. The used flax fibre net is shown in (Fig.1). The textile fabric was processed with resin systems in an industrial impregnation process.

For the impregnation, an epoxy resin with reference SR GreenPoxy 56 (Sicomin) was utilised. The resin component has a density of 1,198 g/cm^3 at 20 °C and a viscosity of approximately 1600 ± 300 mPa·s (at 25 °C approx. 950 ± 190 mPa·s). Note that the bio-based carbon content of the resin component is typically ≈51% [17].

Tecosit CC1000 (CHT) was considered as an additional impregnation. Tecosit binders are designated by the manufacturer as film formers/ polymer systems for coatings

and textile concrete applications. The thermoformability of the cured polymer dispersion on carbon textiles enables the production of three-dimensional geometries (e.g., shear grids) from flat surface structures.

Afterwards, the impregnated powerRibs fabric was characterised by means of tensile tests. The results for a single strand in the direction of force are displayed in Table 1. The cross-section of a single strand was calculated from the fineness of the unimpregnated yarn and the corresponding density. Although the actual cross-section increases as a result of impregnation, only the yarn cross-section was considered for the tensile strength assessment. Note that only the yarn contributes effectively to the tensile strength.

Table 1 Characterisation of the tested textile reinforcement, values for one strand.

Specimens	Number of test specimens	Fineness [tex]	Density [g/cm^3]	Cross-sectional area [mm^2]	Tensile strength, mean value [N/mm^2]	CoV [%]
Flax-Greenpoxy	11	3000	1.4	2.1	392.4	12.75
Flax TECOSIT CC1000	12	3000	1.4	2.1	244.1	15.3

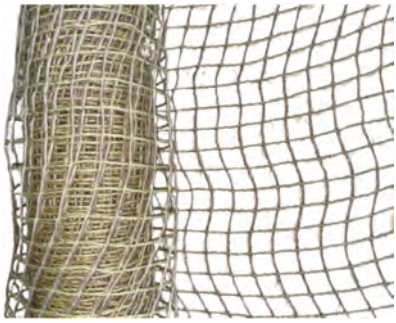


Fig. 1 Used textile made from flax fibres

3 Experimental Investigation

3.1 Test Setup and Procedure

The experimental programme is similar to [18, 19] grounded in the international standard ISO 10406-1 [20]. However, in contrast to [19], this study does not examine the influence of concrete cover on the durability of reinforcement; rather, it focuses on the influence of different impregnations. The document "Fibre-reinforced polymer (FRP) reinforcement

of concrete – Test methods – Part 1: FRP Bars and Grids" [20] delineates a range of methodologies for the evaluation of FRP materials. In this section, a detailed exposition of a methodology for the determination of the alkaline durability of fibre-reinforced polymer (FRP) components is offered. In accordance with the established protocol, individual strands of the reinforcement shall be immersed in an alkaline bath for a duration of 30 days. The pH value of the bath is required to exceed 13, while the temperature is to be maintained at 60 °C ± 3 °C. After this exposure period, the tensile strength of the material shall be measured and compared with reference specimens that have not undergone alkaline immersion.

In the present study, several modifications to the standardised procedure were necessary. Since isolating and gripping a single textile strand was not feasible, the reinforcement was embedded in concrete tensile specimens (see Fig. 2). This approach was chosen to realistically account for the interaction between the textile reinforcement and the surrounding concrete, as it occurs in practical applications. The specimen geometry adheres to the recommendations outlined in [17] and has undergone validation procedures.

To ensure that the alkaline solution could directly reach the hemp-fibre reinforcement, each specimen was preloaded to induce at least two cracks.

Subsequently, five to six specimens of every configuration were subjected to submersion in the heated alkaline solution (pH $>$ 11) for a period of 30 days. During this conditioning phase, both temperature and pH levels were meticulously monitored and adjusted as necessary. A second set, comprising five to six specimens with identical configurations, was stored under standard laboratory conditions (23 °C, 42% relative air humidity) to serve as a reference.

After the completion of the 30-day conditioning period, tensile tests were conducted. The specimens were mounted in a defined clamping zone between two steel plates (see Fig. 2). To enhance the grip, the plates were separated from the concrete surfaces by means of rubber strips. To circumvent premature failure in the clamping region, the tightening torque of the screws was incrementally applied. The first pair of screws near the transition area was tightened to 20 Nm and the following once with 25 kNm. The specimens were, then, loaded in tension at a constant rate of 1 mm/min until failure, while force and displacement were continuously recorded.

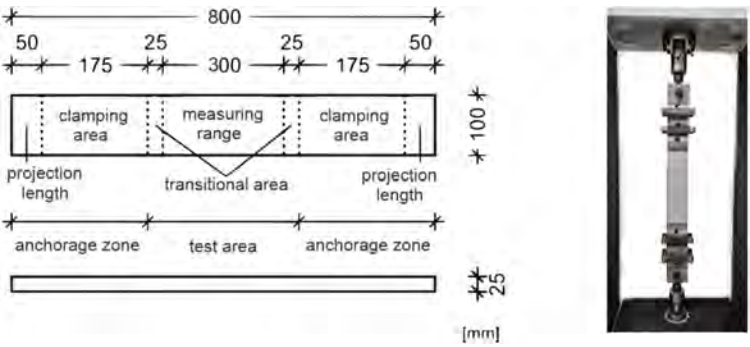


Fig. 2 Tensile test specimen

3.2 Test Results

The tensile strength of the specimens was investigated after different storage conditions, with the reduction in tensile strength being the decisive parameter for the evaluation. The flax textile reinforcement, which consists of 12 strands in longitudinal direction per test specimen, was examined using two different impregnation systems and a concrete cover of 5 mm.

Table 2 indicates that the specimens that had been reinforced with flax textiles impregnated with Greenpoxy exhibite an average reduction in tensile strength of 14.0%. In contrast, specimens with flax reinforcement impregnated with Tecosit CC1000 demonstrated a reduced average reduction in tensile strength of 8.5% under equivalent concrete cover conditions. The empirical coefficient of variation obtained from the tensile tests ranged between 4% and 7% for the specimens with the stiffer Greenpoxy impregnation, indicating a low scatter of the test results. For the specimens impregnated with the softer Tecosit CC1000 system, the coefficient of variation was higher, ranging from 10.7% to 13.3%. This reflects a moderate variability of the measured tensile strengths.

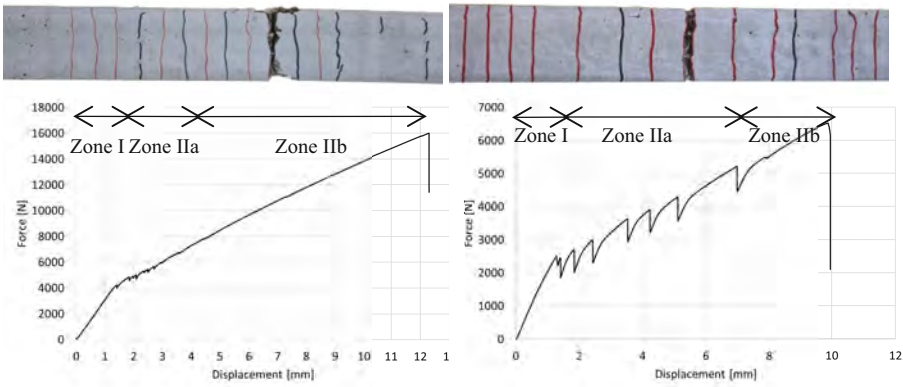
The force-displacement behaviour exhibited by the tensile tests demonstrated characteristic distinctions between the two reinforcement systems. For specimens reinforced with flax textiles impregnated with Greenpoxy, a typical response of textile-reinforced concrete was observed as seen in Fig. 3a, which can be divided into three distinct states. In State I (uncracked), the applied load was predominantly carried by the concrete matrix. State IIa was characterised by multiple cracking, during which both the concrete and the textile reinforcement contributed to load transfer, accompanied by progressive crack formation. In State IIb a stabilised crack pattern was achieved, meaning that virtually no new cracks formed and only the existing cracks continued to widen. In this phase, the material exhibited an approximately linear behaviour with reduced stiffness, while the reinforcement carried increasing load up to its maximum tensile capacity.

Table 2 Results of the durability tests.

Test specimen	Storage	Number of test specimens	Tensile strength [kN]	Breaking strength [N/mm^2]	CoV [%]	Reduction of tensile strength [%]
Flax Greenpoxy	Standard	6	16.2	6.55	4	14.0
	Exposed	5	13.9	5.61	7	
Flax Tecosit CC1000	Standard	6	7.1	2.87	10.7	8.5
	Exposed	6	6.5	2.63	13.3	

In contrast, specimens reinforced with flax textiles impregnated with Tecosit CC1000 did not develop a fully stabilized crack zone corresponding to State IIb (see Fig. 3b). This behaviour is attributed to the lower tensile strength of the flax reinforcement with TECOSIT CC1000 compared to the Greenpoxy-impregnated system. However, both reinforcement systems resulted in a distributed crack pattern along the entire length of the specimens. In Fig. 3, the cracks from the marking are shown in *black* and the cracks

after storage in the alkali bath are shown in *red*. It is noticeable that the crack spacing is larger for the acrylate-based system, which indicates a weaker bond compared to the Greenpoxy matrix.



a) Greenpoxy test specimen with completed zone IIb

b) Tecosit CC1000 test specimen with incompletely zone IIb

Fig. 3 Force-Displacement diagram of a tensile test on flax test specimen

4 Conclusion

The results from this investigation indicate that targeted impregnation strategies can substantially enhance the durability of natural fibre textiles in alkaline concrete environments. The overall reduction in tensile strength observed after accelerated ageing is comparatively low, averaging approximately 11%. These results highlight the promising potential of natural fibres for structural applications in the construction sector.

The extent of strength degradation is strongly influenced by the type of impregnation employed. Textiles treated with Greenpoxy exhibited a relatively higher reduction in tensile strength of up to 14.0%, whereas specimens impregnated with Tecosit CC1000 showed a lower decrease of around 8.5%. Nevertheless, despite the higher relative strength loss, the Greenpoxy system demonstrated a higher absolute tensile strength and a more stable crack development. This findings suggest that for the evaluation of material performance, information on percentage strength loss, as well as on the absolute load-bearing capacity and crack behaviour of the composite system is needed.

Furthermore, the experimental results show that concrete reinforced with natural fibre textiles has load-bearing properties similar to those of textile-reinforced concrete, characterised by multiple cracking and effective stress transfer. For both impregnation systems addressed in this investigation, a uniform crack distribution over the entire specimen length was observed, indicating a reliable bond between the textile reinforcement and the concrete matrix.

In conclusion, this study provides a fundamental contribution to the understanding of the durability behaviour of impregnated natural fibre textiles in cementitious environments. The findings establish a solid foundation for future research, including investigations into long-term durability, cyclic loading effects, and the development of more sustainable impregnation systems that maintain mechanical performance while further reducing the environmental impact of textile-reinforced concrete.

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Circular Assessment of Arctic Timber Façades: Integrating Solar Analysis, Active Hyperspectral Sensing, and Ground-Penetrating Radar

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Abstract. Timber is widely used in Arctic construction, yet its long-term durability is challenged by harsh environmental exposure, where solar radiation accelerates surface degradation (due to extreme seasonal variations) and logistical constraints to remote areas highlight the importance of material reuse within circular construction strategies. This study evaluates the condition of timber façade elements in Svalbard (Norway) across three façade orientations (scenes C, F, and G), integrating solar irradiance analysis with Active Hyperspectral Sensing (AHS) to detect variations in reflectance associated with surface weathering, discoloration and early-stage material damage, and Ground-Penetrating Radar (GPR) to characterize internal conditions and identify subsurface anomalies. While solar exposure levels were comparable between scenes C and G, the integrated sensing approach identified significant moisture-induced deterioration and internal clutter in scene C, contrasting with the structural integrity preserved in scenes F and G.

Keywords: solar geometry · non-destructive testing · building façade analysis · urban mining · circular construction · sustainability

1 Introduction

The Arctic region is currently facing unprecedented climate warming, leading to permafrost degradation that severely threatens the capacity and structural integrity of public infrastructure [1]. This environmental crisis demands a transition toward a Circular Economy, a paradigm that seeks to decouple economic growth from environmental degradation by keeping materials at their highest utility while respecting planetary boundaries [2]. Within the framework of Industry 5.0, which emphasizes sustainability and resilience, forest products emerge as vital renewable alternatives to carbon-intensive materials, offering significant potential for climate change mitigation and long-term carbon storage [3]. However, the successful conservation of wood into the Arctic built environment requires advanced information sharing and data standards across supply chains to manage the estimated US$ 132 billion in potential economic losses caused by thawing grounds by 2050 [1].

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Wood long-term durability is significantly challenged by natural aging processes, with solar radiation identified as the primary catalyst for surface degradation. Specifically, ultraviolet (UV) radiation triggers photodegradation, which leads to immediate aesthetic changes such as yellowing and reddening, alongside the chemical breakdown of lignin and hemicellulose. While these effects are initially concentrated on the surface layer, they are often accelerated by synergistic factors like temperature and moisture, eventually causing microstructural damage such as cracks and cell wall deformations. Quantifying sun-induced degradation is therefore a critical task for ensuring the safe service and effective maintenance of both modern timber systems and ancient architectural heritage [4].

This research aims to investigate the degradation of timber triggered by the unique solar radiation patterns characteristic of Arctic regions. This study analyzes wood specimens collected from Svalbard, Norway, across various orientations to account for specific solar exposure angles. To achieve a comprehensive multiscale assessment, a dual Non-Destructive Testing (NDT) approach was implemented: an Active Hyperspectral Sensor (AHS) was utilized to quantify surface-level aging and colorimetric changes, while Ground Penetrating Radar (GPR) was employed to evaluate structural integrity and moisture-related alterations in deeper layers. This integrated methodology seeks to understand the synergistic effects of radiation, extreme temperatures, and moisture on the long-term durability of wood in high-latitude environments.

2 Materials and Methods

2.1 Case Study

The case study is in a residential building in Longyearbyen, Norway. The structure is constructed primarily of timber, and three areas (C, F, and G) were scanned for analysis. The location and orientation of the samples are presented in Fig. 1.



Fig. 1. Location and orientation of scenes C, F and G.

Samples F and G are located on the northwest facade of the building at ground level, whereas sample C is situated on the south-facing terrace on the second floor.

2.2 Solar Irradiance Analysis

Solar irradiance analysis was performed using the ShadeMap tool to assess sunlight exposure and shadow distribution across the building facades under study. ShadeMap is a global shadow simulation platform that calculates shadow positions in real time based on sun position for any given date, time, and geographic location. For each map pixel, the tool traces a path toward the sun and determines whether it is intercepted by a building, tree, or terrain feature, classifying the pixel as shaded/sunlit accordingly [5].

Building geometry data was sourced from OpenStreetMap, the Overture Maps Foundation, and Mapbox Streets. It should be noted that the shadow estimates rely on data gathered through indirect methods, including crowdsourcing and machine learning models, which may introduce positional errors of up to several meters. Despite this limitation, the tool provides a reliable general characterization of shadow distribution and sun direction across the analyzed facades, both on a daily and annual basis.

2.3 AHS Data Collection and Processing

Regarding the AHS analysis, the equipment was deployed on-site, capturing outdoor images of the building under study. Seven different scenarios in the building were imaged, varying the location and sunlight exposure as described in Table 1.

Table 1. Summary of scenarios analyzed and sample qualitative description.

Scene ID	Description	Scene ID	Description
C	Plywood; Partially shaded	H1	Untreated Timber; Direct sunlight
D, E	Plywood; Shaded	H2	Untreated Timber; Direct sunlight
F	Cladding; Shaded	J2	Cladding; Directly sunlight?
G	Cladding; Direct sunlight		

Data were acquired using a VTT AHS imaging system (1300–1650 nm spectral range) both on-site and in laboratory conditions, with a spectral resolution of 12–18 nm. Measurements were conducted in a point-scan configuration, with the sensor positioned at approximately 3 m from the target. Specim SWIR camera (1000–2500 nm) was also employed in laboratory conditions for comparison, since this equipment has a lower field of view (12 cm), but higher spectral resolution (12 nm).

From the scenes imaged, 10 samples of wood disks (~25 mm diameter) were also obtained from the building. Both sides were also imaged in laboratory conditions to evaluate differences between wood from different scenarios. Only unpainted surfaces of the scenarios were analyzed.

Afterward, Principal Component Analysis (PCA) was carried out to investigate sources of variability and to identify patterns or clustering within the hyperspectral dataset [6]. This approach is an unsupervised method and therefore does not rely on prior reference information to define clusters. As a result, this technique is well suited for exploring the intrinsic structure and variability of the measurements prior to comparison with reference datasets.

2.4 GPR Data Collection and Processing

The GPR system that was used is the high-frequency GP8800 probe which is a step-frequency continuous-wave (SFCW) transducer with a modulated frequency range of 400–6000 MHz. This is a GPR antenna with high resolution that can resolve small features and has a maximum penetration depth of ~65 cm. The penetration can vary based on the material conditions of the surveyed structure, but this did not pose a limitation considering the small thickness of the walls and floors of the building. Both the transmitter Tx and receiver Rx are included in a single enclosure. The dimensions of this probe are 8.9 × 8.9 × 7.6 cm and its weight is ~500 g and can be operated at temperatures between 5° and 40°. It is further equipped with a replaceable skid plate used for protecting from damage. The device is controlled using an iPad via an application called GP app. Connectivity between the two is established via Wi-Fi or via a USB-C cable. Although the main application for this probe is concrete inspection, used to locate key structural elements, such as rebars, post-tension cables, and conduits or for concrete characterization, it has been also used for other applications where high resolution is required, such as wooden pole inspections [7].

Both external and internal scans to the building were performed, from the external cladding and the internal fibre board side, respectively, with the external ones presented here. The walls consist of different layers including cladding, asphalt panels, insulation layers, fibre board but also multiple wooden studs and therefore different responses from those were expected.

At each location, a 60 × 60 cm area scan was conducted where line measurements were collected in both x and y directions with a 5 cm spacing, resulting in a total of 26 lines. To mark the scanning area, measurement lines and spacings, a grid paper with marked lines was used, which was attached to each scanning location. The system was in direct contact with the wood surface during scanning. The locations of the scans along with the GP8800 are shown in Fig. 2. In most cases, the raw GPR data requires some processing before starting the interpretation process. Therefore, after data collection, the following processing filters were applied in sequence:

- Time zero correction: Vertical shift used for correct depth estimation.
- Noise cancellation: Frequency filter used for removing noise in the data.
- Background removal: Used to remove banding noise and the strong surface response that might mask other objects.
- Gain: Used to amplify the signal amplitudes

3 Results and Discussion

3.1 Solar Irradiance

Analysis of the results reveals variability in annual solar irradiance across scenes C, F and G. Although scenes C and G exhibit comparable levels of solar intensity, scene F is clearly distinguishable from both. This is consistent with the spatial configuration of the facades: scenes C and G are located on the same building facade, whereas scene F is situated on the adjacent facade, separated by a 90° corner, with the building itself partially obstructing its solar exposure (Fig. 3).



Fig. 2. Locations of the 3 external scans along with the GP8800 system and grid paper used for marking the area: a) Area C, b) Area F and c) Area G.

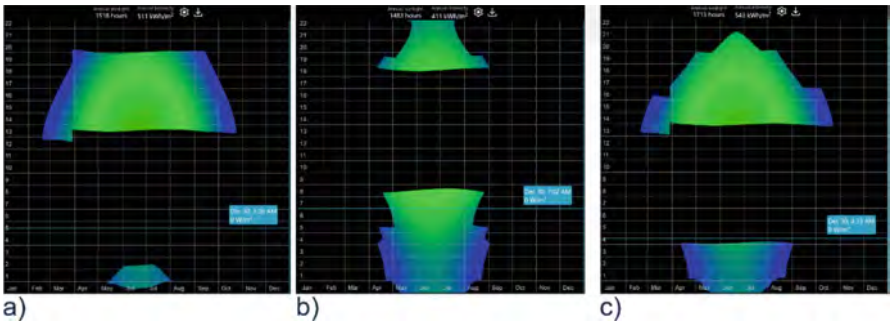


Fig. 3. Annual Sunlight Intensity from ShadeMap: Hour of the day vs. day of the year, while color shows intensity at that time. a) Area C, b) Area F and c) Area G.

3.2 AHS Results

Analyses based on data acquired with the AHS hyperspectral camera did not reveal significant differences among scenes C, F, and G, neither for reference samples (disks) nor for field samples. In contrast, principal component analysis (PCA) of data obtained with the Specim camera showed trends in the scores plot, differentiating reference samples from scene C from those of scenes F, G, D, and E. The spectral regions contributing most strongly to this separation were associated with moisture absorption features (~1410 and 1900 nm) and bands in the 2000–2500 nm range related to vibrational modes of cellulosic compounds [8]. This latter spectral range is not covered by the AHS sensor, which may explain the absence of corresponding differences in the AHS data.

Both hyperspectral systems were able to successfully capture differences associated with moisture-related damage, particularly on scenario H2 (Fig. 4c). Those consisting of untreated timber samples from an outdoor fence exposed to varying degrees of sunlight and moisture. The visibly damaged sample from scene H2 differed significantly from the remaining samples (PCA scores plot in Fig. 4a, d), with the dominant source of variability again linked to moisture spectral regions (Fig. 4b).

Overall, data variability was more pronounced in the field measurements acquired with the AHS camera. This can be explained by the larger areas evaluated compared to the laboratory reference samples (small disks), as well as the acquisition conditions.

Nevertheless, field data acquired with the AHS camera provided valuable information about wall damage, particularly related to moisture effects.

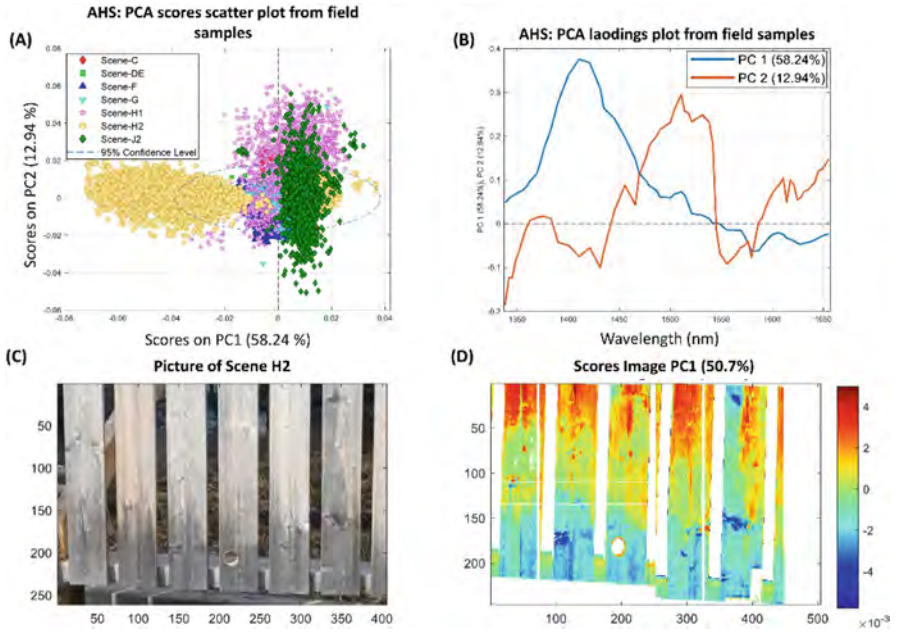


Fig. 4. On-site analysis with AHS: PCA (a) scores scatter plot and (b) loadings plot from field samples of different scenarios; (c) false-color image of scenario H2; PCA (d) scores image.

3.3 GPR Results

Although multiple line scans were collected at each location, a representative B-scan from each is discussed here and presented in Fig. 5. In area C, significant clutter was present in the GPR data from within the wall, which is highlighted in the corresponding B-scan in Fig. 5a. This clutter is indicative of higher moisture content and/or potential voids in the wall and therefore, in this case it can be considered that the wood structure in this area is deteriorated. This observation can also be correlated with the damaged coating at the wood surface.

In both F and G areas, the wood studs, the asphalt panel/insulation interface and the response from the backwall could be identified. In contrast, apart from responses from different objects and layers within the wall, no significant clutter or other anomalies were observed in the data, indicating that the wood in these parts of the building is in good condition, with examples of B-scan data from each area shown in Figs. 5b and 2c, respectively.

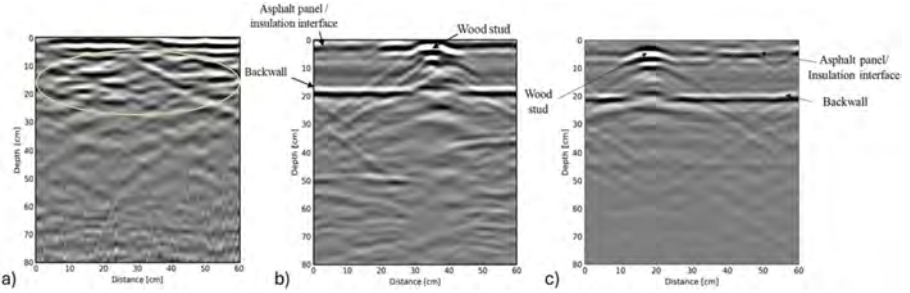


Fig. 5. GPR B-scan results: a) Location C showing significant clutter, b) Location F with annotated responses and c) Location G with annotated responses.

3.4 Correlation and Discussion

The integrated analysis of scenes C, F, and G reveals a clear correlation between environmental exposure and material condition. While solar analysis shows that scenes C and G experience comparable levels of annual solar intensity, scene F is distinct due to its spatial configuration and partial obstruction by the building itself. Despite the similar solar radiation on C and G, GPR identifies significant internal clutter and moisture in scene C, suggesting advanced deterioration, whereas scenes F and G remain in good structural condition. This is further supported by AHS results, which differentiated scene C based on spectral signatures associated with moisture absorption and the breakdown of cellulosic compounds. Consequently, the deterioration in scene C, which is also visible through its damaged surface coating, highlights how synergistic factors like high solar exposure and moisture can accelerate timber degradation in Arctic environments.

4 Conclusion

Beyond ensuring durability and facilitating wood reuse, this study integrated multi-layered sensing technologies to advance the Circular Economy by operationalizing digital urban mining and material bank creation. By providing high-resolution, non-destructive assessments of material health prior to deconstruction, this methodology enables informed reuse decisions, treating timber as a traceable resource within circular supply chains rather than waste. The differentiation between deteriorated and structurally sound timber elements exemplifies how NDT data can directly support material grading and selective reuse strategies. This data-driven approach supports advanced information sharing across supply chains, ensuring that forest products are kept at their highest utility and value.

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Utilization of Tire Recycling Waste in Construction Composites

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Abstract. The use of tire recycling waste in construction composites reveals sustainable opportunities in civil engineering. Research has shown that shredded tire rubber, used as a partial replacement for fine aggregate, reduces the compressive strength and modulus of elasticity of concrete, but has little effect on flexural and splitting strength, while significantly improving frost resistance. For example, replacing 2.5% of fine aggregate with rubber decreases compressive strength by about 13.6%, yet the flexural strength differs by less than 5% compared to control concrete. Steel cords and wires from tires, applied as dispersed reinforcement, demonstrate high tensile strength (1871–2491 MPa), exceeding that of certified steel fibers (~1200 MPa), and can therefore be rationally used as substitutes. Test results indicate that concrete reinforced with such cords achieves 8–25% higher flexural strength than control concrete reinforced with certified fibers. Overall, tire recycling waste—rubber and steel cords—can be successfully applied in sustainable concrete production, contributing to solving ecological pollution issues. However, the amount of rubber in the mixture must be limited to avoid deterioration of the main mechanical properties of concrete.

Keywords: Recycled Tire Waste · Construction Composites · Dispersed Reinforcement · Steel Fibers

1 Introduction

The continuously increasing global volume of end-of-life tires poses notable environmental challenges, as these products are highly resistant to biodegradation, occupy significant landfill space, and when improperly stored, may cause fires and release hazardous substances. Consequently, many countries have introduced stricter regulations limiting tire disposal in landfills and promoting their recycling and reuse [1]. According to data from the United States in 2015, approximately 49% of used tires were utilized

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as alternative fuel, 26% were processed into rubber crumbs, 11% were landfilled, and only 6% were applied in civil engineering applications [2]. By 2019, the share used in the construction sector had increased to around 8%, demonstrating the rising relevance of this utilization pathway [3].

Over recent decades, tire recycling technologies have advanced considerably. Multistage mechanical, mechanic-chemical, and thermal treatment methods now allow the effective separation of rubber, steel cords, and textile components [4–6]. These processes generate various rubber filler fractions—chipped, shredded, granulated, ground, or fibrous [7]—which can be used as partial replacements for fine or coarse aggregates in concrete. The recycling process also yields steel cords (see Fig. 1) [8], whose mechanical properties, in certain cases, approach those of commercial steel fibres [8, 9].

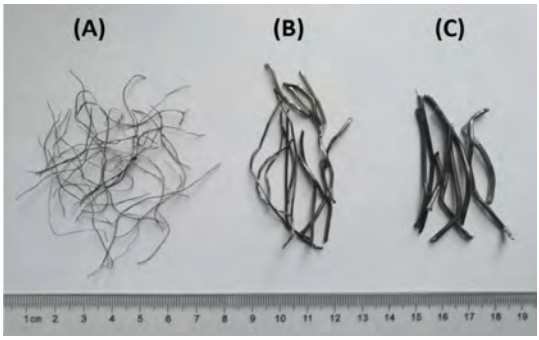


Fig. 1. Steel cords from tire waste: (A) cross-section 0.30–0.35 mm; (B) cross-section 0.70–1.40 mm; (C) cross-section 1.45–2.10 mm.

Given that concrete is the most widely used construction material globally and requires substantial quantities of natural resources [7], the integration of tire derived materials into concrete technology is regarded as a sustainable approach that reduces the consumption of primary raw materials. Nevertheless, the incorporation of rubber into concrete induces complex changes to its properties. As rubber content increases, the density of concrete decreases due to the lower specific gravity of rubber, while both porosity and water absorption increase [8, 10]. Microstructural investigations further indicate a weaker bond between rubber particles and the cement matrix, as well as the formation of microcracks within the interfacial transition zone (see Fig. 2) [11].

Consequently, increases in rubber content commonly lead to reductions in compressive strength and modulus of elasticity [11–13]. Despite this, selecting an appropriate replacement level may preserve adequate load bearing capacity for non-structural or lightly loaded elements [14]. On the other hand, rubber modified concrete exhibits several advantageous performance characteristics. A reduction in thermal conductivity has been widely reported [8], along with notable improvements in impact resistance. When particle size is appropriately selected, enhanced freeze–thaw resistance may also be achieved [13]. Additionally, some studies indicate satisfactory behaviour at elevated temperatures, although outcomes remain mixture dependent.

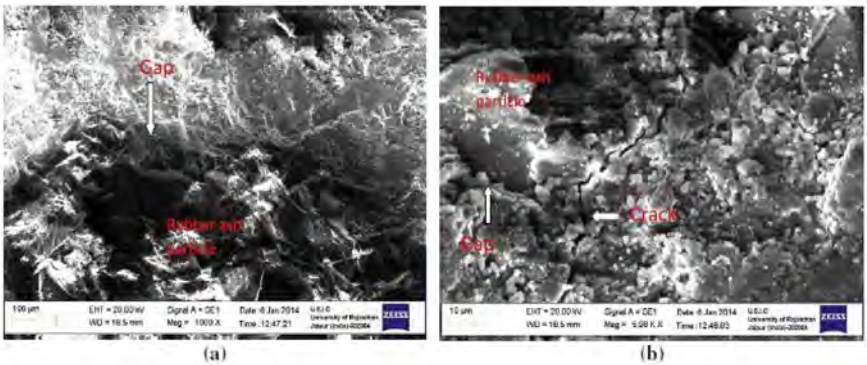


Fig. 2. Microstructural analysis of modified concrete containing 20% rubber ash at a water to cement ratio of 0.45. Magnification: (a) 1000×; (b) 5980× [11].

To address the reduction in mechanical performance, dispersed fibre reinforcement is frequently employed. Such reinforcement effectively limits crack propagation, reduces crack width, and enhances residual tensile strength [15]. Within this context, steel cords recovered from end of life tires represent a promising alternative to commercial steel fibres, as their mechanical characteristics allow them to reinforce concrete effectively and improve post cracking behaviour [8, 9].

The aim of the study is to evaluate how the combined use of rubber aggregates and steel cord reinforcement can compensate for the reduction in compressive strength, increase ductility, and improve resistance to dynamic loading. By integrating both rubber fractions and steel cords from waste tires into concrete, the study seeks to demonstrate that such an approach is well-justified from both sustainability and structural performance perspectives

2 Materials and Methods

2.1 Raw Materials and Methods

Conventional heavy-weight concrete was used in the study, with the mix composition designed to evaluate the influence of recycled tire rubber waste and steel fibers (commercial fibers and tire steel cords) on the mechanical and performance properties of concrete. Portland cement CEM II/A-LL 42.5 N, compliant with the requirements of EN 197-1:2011, was used as the binding material. Natural aggregates were used in accordance with EN 12620:2003 + A1:2008: sand with a 0/4 mm fraction (particle density 2650 kg/m^3 and bulk density 1600 kg/m^3) and dolomite gravel with a 4/16 mm fraction (particle density 2800 kg/m^3 and bulk density 1400 kg/m^3). Potable tap water was used for mixing, and the workability of the mixtures was adjusted using the superplasticizer Sika Viscocrete D187 (18%).

In part of the mixtures, natural aggregates were partially replaced with recycled tire rubber aggregate obtained through mechanical recycling (see Fig. 3). Considering the influence of rubber particle size and amount on concrete properties discussed in the

literature [7, 11], shredded rubber with a particle size of approximately 0.05 mm was used in the study. It was applied as a partial replacement for fine aggregate, not exceeding 2.5% of the total aggregate mass i.e., the sum of fine and coarse aggregates, with only the fine fraction being replaced.

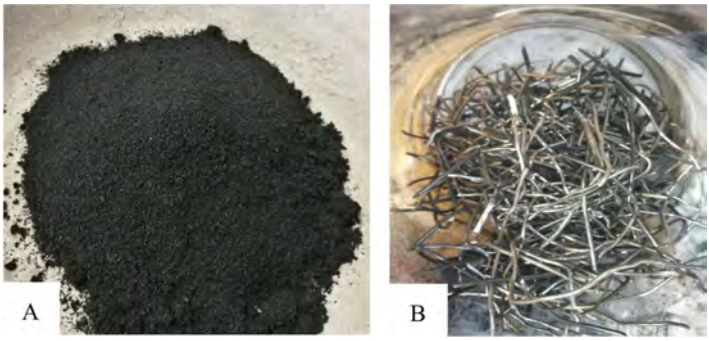


Fig. 3. Materials used in the study: (A) shredded tire-waste rubber obtained from recycled tires; (B) recycled tire steel cords.

In addition to rubber, steel fibres were used in the study: commercial steel fibres (Ø = 1.0 mm) and tire steel cords obtained during recycling. The cords were classified into three groups according to diameter (1.5 mm, 0.8 mm, and 0.35 mm). Their geometry (round cross-section, length ~50–70 mm) allowed comparison of the influence of steel elements of different origin and diameter on the behaviour of fibre-reinforced concrete (see Fig. 3). Standard steel moulds were used for specimen fabrication, and all specimens were cured under controlled conditions for 28 days. Standardized test methods were applied to determine the mechanical and performance properties of concrete. Compressive strength was determined according to EN 12390-3:2009 using 100 × 100 × 100 mm cubes (EN 12390-1) and a hydraulic press "Toni Technik 2020," compliant with EN 12390-4. The flexural (residual tensile) strength of fibre-reinforced concrete was determined according to EN 14651:2005 + A1:2007 using 100 × 100 × 400 mm prisms with a central notch and a 300 mm span. During testing, crack mouth opening displacement (CMOD) was recorded, and residual strength values were determined at CMOD = 0.5, 1.5, 2.5, and 3.5 mm. Splitting tensile strength (also used to evaluate bond performance in layered specimens) was determined according to EN 1338:2003 + AC:2006 using 100 × 100 × 100 mm cubes with load applied through distribution strips. The mechanical properties of the steel fibres (commercial fibers and tire cords) were evaluated by tensile testing according to EN ISO 15630-1:2019 and ISO 6892-1:2019 using a universal tensile testing machine. Concrete frost resistance was evaluated according to LST 1428-17:2017 using 100 × 100 × 100 mm cubes. Prior to testing, the specimens were saturated with water and subjected to freeze–thaw cycles in a freezing chamber (−20 °C). The specimens were examined after 150, 200, and 250 (up to 275) cycles by assessing mass loss and changes in compressive strength. Frost resistance was considered sufficient when the reduction in compressive strength did not exceed 5%.

The selected materials and testing methods enabled evaluation of the influence of crumb rubber as a partial aggregate replacement on density, strength, stiffness, and frost resistance, and the effect of commercial steel fibers and recycled tire cords on the post-cracking behavior of concrete by assessing residual flexural strength and fiber mechanical properties.

2.2 Concrete Mix Design and Preparation

The mix proportions of the control and modified concrete mixtures used in this study are presented in Table 1. All mixtures were designed using the same base composition, and the consistency classes of the mixtures ranged from S2 to S3. A constant dosage of superplasticizer (2.7 kg/m^3) was used in all mixtures. The modifications were introduced by incorporating recycled tyre cord fibres of different diameters or by partially replacing fine aggregate with crumb rubber. The fibre dosage was kept constant at 30 kg/m^3 in all fibre-reinforced mixtures. In the rubberized concrete mixture, 2.5% of the fine aggregate mass was replaced with crumb rubber particles, and no fibres were used in this mixture.

Table 1. Mix proportions of concrete with tire cord fibers and crumb rubber (per 1 m^3)

Mixture ID	Cement (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Water (kg/m^3)	Slump (mm)
C	340	970	870	170	150
CF-30	340	970	870	170	90
TC (1.4–2.1)	340	970	870	170	90
TC (0.7–1.4)	340	970	870	170	80
TC (0.35)	340	970	870	170	60
R-2.5%	340	970	~848	170	120

C – control concrete; CF30 – concrete with commercial steel fibres (30 kg/m^3, Ø ≈ 1 mm); TC – recycled tire cord fibres (diameter range in mm, fibre dosage 30 kg/m^3); CR2.5 – concrete with crumb rubber replacing 2.5% of fine aggregate (by mass of total aggregates); TC (0.35) – mixtures with fine tire cord fibres (Ø ≈ 0.35 mm).

Concrete specimens were produced using the mixtures listed in Table 1. A total of standard cubes (100 × 100 × 100 mm), prisms (100 × 100 × 400 mm), and layered beams were cast for mechanical testing. The prepared specimens used in the experimental program are shown in Fig. 4.

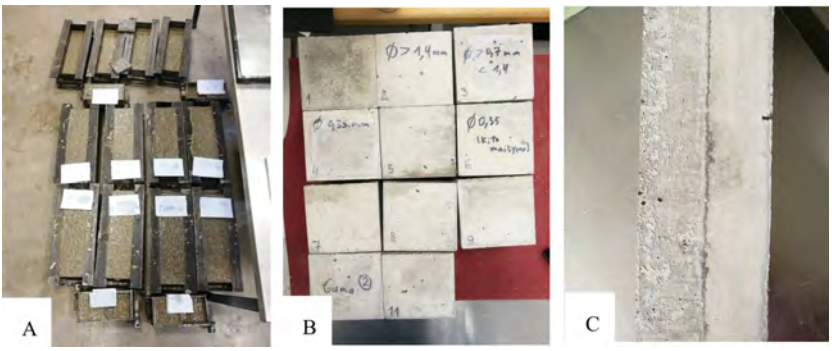


Fig. 4. Concrete specimens prepared for experimental testing: (A) cubes (100 × 100 × 100 mm; (B) prisms (100 × 100 × 400 mm); (C) layered beams.

3 Results and Discussions

After 28 days of curing, the density and mechanical properties of the tested concretes were determined. All investigated mixtures can be classified as normal-weight concrete, with average densities ranging from 2316 to 2403 kg/m^3. The lowest density was obtained for the rubber-modified concrete in which 2.5% of the fine aggregate was replaced with crumb rubber. Compared with the control concrete, the density decreased by approximately 3.6%, which can be explained by the lower specific weight of rubber particles compared with mineral aggregates. The highest compressive strengths were obtained for the concrete reinforced with commercial steel fibres and for the concrete reinforced with fine recycled tyre cord fibres (Ø ≈ 0.35 mm), reaching 51.71 MPa and 51.36 MPa, respectively (see Table 2). The control concrete without fibres and rubber reached 49.08 MPa, while mixtures reinforced with larger tyre cord fibres showed similar compressive strength values (48.68–49.08 MPa). These results indicate that recycled tyre cord fibres can provide compressive strength comparable to commercial fibres. In contrast, the use of crumb rubber reduced the compressive strength to 42.61 MPa, corresponding to a decrease of approximately 10–15%. This reduction is mainly attributed to weaker bonding between rubber particles and cement paste and the lower stiffness of rubber compared with mineral aggregates.

Flexural tests showed that the first crack strength was similar for most fibre-reinforced mixtures, indicating that fibre diameter had a limited influence on crack initiation. However, the distribution of fibres in the concrete significantly affected the post-cracking behaviour. Larger tyre cord fibres resulted in greater scatter of the results due to the smaller number of fibres per unit volume.

Tests of layered beams demonstrated sufficient bond between the layers, and the presence of a rubber-modified upper layer reduced the crack initiation strength only slightly (about 5%).

Additional tests revealed that the finest tyre cord fibres (Ø ≈ 0.35 mm) had the highest tensile strength (≈2492 MPa), exceeding that of larger cords and being comparable to commercial steel fibres. The elastic modulus of rubber-modified concrete was approximately 15% lower than that of conventional concrete. Freeze–thaw tests showed that all

Table 2. Physical and mechanical properties of the tested concrete mixtures

Mixture ID	Density (kg/m^3)	Compressive strength		Flexural tensile strength (MPa)
		after 28 days (MPa)	after 275 freeze–thaw cycles (MPa)	
C	2403	49.08	49.12	–
CF 30	2377	51.71	–	3.82
TC (1.4–2.1)	2375	48.68	–	4.39
TC (0.7–1.4)	2338	49.08	–	4.15
TC (0.35)	2362	51.36	55.72	4.05
CR 2.5	2316	42.61	42.89	4.29

mixtures satisfied durability requirements, with compressive strength losses below 5% after 200–275 freeze–thaw cycles. Overall, the results indicate that crumb rubber can reduce concrete density while maintaining adequate durability, whereas recycled tyre cord fibres can be used as an alternative to commercial steel fibres.

4 Conclusions

The results of the study demonstrate that recycled tire waste can be effectively used in concrete mixtures, particularly through the application of steel cords and wires. Steel cords recovered from tire waste can successfully serve as dispersed reinforcement in concrete or reinforced concrete, and concrete reinforced with these elements achieved flexural strength comparable to or higher than that of concrete reinforced with certified steel fibers. Depending on the cord diameter, the flexural strength ranged from 5.1 to 6.2 MPa, which is 8–25% higher than the average value obtained using certified fibers (4.7 MPa). In addition, tire cords exhibit very high tensile strength, ranging from 1871 to 2491 MPa, which exceeds the declared tensile strength of certified steel fibers ($\geq$1200 MPa), indicating that they can be considered a viable alternative reinforcement material. The incorporation of rubber particles into concrete mixtures also improved the frost resistance of concrete, as the reduction in compressive strength after freeze–thaw cycles was lower compared with control specimens, while the influence of rubber on flexural and splitting tensile strength was minimal. However, some negative effects were observed: replacing 2.5% of fine aggregate with crumb rubber reduced compressive strength by approximately 13.6%, and the use of rubber also decreased the modulus of elasticity of concrete by about 15% compared with the control concrete. Overall, despite certain reductions in mechanical properties, tire waste components—particularly steel cords—demonstrate significant potential as alternative reinforcement materials.

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Material Innovation in Bio-Based Construction: Development of Straw Composite Blocks with Enhanced Mechanical Performance

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Abstract. Reliable material properties for bio-based materials are essential for their contemporary application in load-bearing construction. Although straw is a regional and readily available, renewable agricultural by-product with low embodied energy, its use in structural applications has long been limited by low mechanical performance, and challenges in standardised fabrication. To address these constraints, this study investigates a novel composite material for densified straw composite blocks, in which straw fibres are combined with organic additives such as spruce shavings and stabilised using lignin as a natural binder. The composite is compacted and subsequently thermally consolidated under pressure to enhance its structural performance. The research integrates experimental material testing with microscopic analysis of the composite bond and sustainability evaluations. Results show that the optimised hybrid composites substantially improve the mechanical performance of conventional straw bales used in construction, demonstrating a significant in-crease in compressive strength (↑~4200 %) and a marked increase in stiffness (↑~5860 %), while also generating highly reliable material properties. Furthermore, the proposed manufacturing process is compatible with industrial prefabrication workflows, enabling efficient, scalable, and low-carbon production. The paper concludes that densified straw composite blocks represent a promising pathway for integrating agricultural residues into modern construction, contributing to climate-resilient and resource-efficient building practices.

Keywords: straw construction · bio-based material innovation · straw composite blocks · agricultural residue utilisation · sustainable building materials

1 Introduction

The construction sector accounts for a substantial share of global CO_2 emissions, with a significant proportion originating from the production of building materials. Within buildings, wall components represent a major share of embodied energy. At the same time, the provision of housing remains a fundamental societal need despite increasing resource scarcity, intensifying the search for construction materials based on renewable resources and low-energy production processes.

Straw has attracted increasing research interest as a bio-based building material due to its wide availability and favourable environmental performance. In Germany,

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approximately 13 million t of surplus straw (fresh mass) are available annually while maintaining a balanced humus budget [1]. At the same time, wood processing generates large quantities of residual materials such as wood shavings. Around 13.3 million t of mobilisable residual wood (dry mass) were available in Germany in 2020 [2]. The utilisation of such agricultural and forestry by-products represents a promising pathway for developing resource-efficient construction materials without additional pressure on primary resources.

One established approach is straw bale (SB) construction, which offers very low primary energy demand and temporary carbon storage. However, its structural application remains limited by low compressive strength, large wall thicknesses, and restricted geometric flexibility resulting from fixed bale dimensions. To overcome these limitations, recent research increasingly investigates engineered straw-based composites with improved mechanical performance. The masonry material investigated in this study, referred to as the Straw Composite Block (SCB), follows this approach and consists primarily of chopped straw combined with spruce wood shavings and lignin as a natural binder. The manufacturing process aims to produce masonry units with defined geometry, improved stiffness, and sufficient load-bearing capacity for applications in low-rise construction. Such applications are particularly relevant in Germany, where the residential building stock is dominated by one or two storey buildings [3]. In addition, approximately 91.5% of the existing residential building stock is older than 15 years [3], indicating a substantial demand for refurbishment and associated wall construction materials.

Despite the growing interest in bio-based construction materials, reliable data on the mechanical performance of straw-based composite masonry products remain limited. To support their adoption in engineering practice, systematic investigations of their mechanical behaviour are required. This study therefore investigates the mechanical properties of the newly developed SCB, focusing on its compressive strength and stiffness compared with conventional SB. In addition, the environmental impact and material-related constructive requirements are investigated.

2 Sate of the Art

SB construction is widely regarded as a circular and environmentally favourable building technique due to its low embodied energy and the renewable nature of the raw material. Nevertheless, straw-based construction remains a niche application, largely due to limitations associated with the material properties and construction method. In Germany, for example, approximately 1800 buildings have been realised using SB systems [1].

Compared with conventional masonry materials, load-bearing SB construction exhibits a very low carbon footprint but also low compressive strength and stiffness. Structural walls typically consist of large bales measuring approximately 40–120 cm in width and 30–270 cm in length. These dimensions introduce construction and detailing challenges, particularly in the design of corners, connections, and defined load paths [5]. In addition, bale geometry is largely predetermined by the agricultural product and cannot easily be modified, limiting architectural and structural flexibility.

The structural performance of SB also remains limited [6], restricting their use in load-bearing applications. Furthermore, the limited availability of standards, design

guidelines, and regulatory approvals constrains the broader adoption of load-bearing straw-based construction [7].

To address these limitations, recent research increasingly investigates engineered straw-based materials and composite products that aim to improve mechanical performance while retaining the environmental benefits of agricultural by-products. Such approaches include straw-based composite boards, fibre-reinforced bio-based panels, and other engineered building products [8–11].

However, compact straw-based masonry units with improved mechanical properties and defined geometries remain comparatively underexplored. The SCB investigated in this study follows this approach by combining chopped straw with wood shavings and lignin as a binder to produce a compact composite masonry element.

3 Methods

3.1 Manufacture Process

For manufacturing, 42 wt.% dust-free wheat straw fibres with a length of approximately 1 cm are used, as shown in Fig. 1a). In addition, 42 wt.% dried and dust-free spruce shavings with a particle size of approximately 1 cm are incorporate (Fig. 1b).



Fig. 1. a) chopped straw, b) spruce shavings, and c) SCB specimen [Photos: Katrin Linne].

Lignin (kindly provided by Mercer Rosenthal GmbH), a by-product of the pulp and paper industry, is used as a powdered binder (4 wt.%). The moisture contents of both straw and wood are determined prior to mixing. Based on these values, a mixture with defined proportions of straw fibres, wood shavings, lignin, and water is prepared. The density of the wood component is measured, and a target compaction density for the mixture prior to thermal stabilisation is defined accordingly.

The mixture is placed in a mould, compacted, and sealed under pressure. Subsequently, the thermal stabilisation of 2 h at 180 °C is applied, consisting of a single heating cycle followed by cooling. After demoulding, the specimens undergo an additional drying phase outside the mould. Test specimens are produced using moulds with a side length of 15 cm, as shown in Fig. 1c).

The measured bulk densities of the spruce shavings span a wet bulk-density range from 255 kg/m^3 up to a dry bulk density of 1418 kg/m^3. For the mixture design, a mean

spruce bulk density of 460 kg/m^3 was adopted in accordance with Richter and Ehmcke [12]. Assuming this value, the constituent proportions and the target bulk density before thermal stabilisation (500 kg/m^3) give a final dried bulk density of the test specimen of 452 kg/m^3, which corresponds to a pre-thermal-treatment straw compaction of 449 kg/m^3.

3.2 Compressive Strength and Modulus of Elasticity

The mechanical compression tests of the SCBs were carried out on the Zwick Roell UTM Z100/S universal testing machine at the Materialforschungs- und -prüfanstalt (MFPA) in Weimar. Mechanical properties are determined after at least 10 days of drying under ambient laboratory conditions, allowing the material to reach equilibrium moisture content. The test protocol was carried out as shown in Table 1, incorporating a 60-s hold period, before the load was released.

Table 1. Mechanical testing settings

Boundary conditions	Attitude
Preload	90 N
Advancement speed?	*15 mm/min*
Temperature | relative humidity	23+/−5 °C | 55 +/−5%
Maximum compressive strain	7%

The compressive elastic relationship is determined following the procedure described in DIN EN 826 [13] for thermal insulation materials used in construction (see Fig. 2).

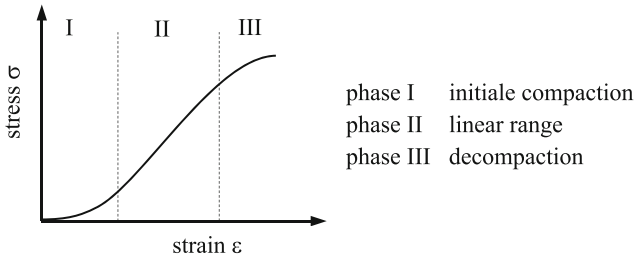


Fig. 2. Typical trend of the short-term compression test curves

The compressive modulus of elasticity (E-modulus) is defined as the ratio of compressive stress to the corresponding strain within the proportional limit, assuming a linear relationship. The linear region in Phase II is used to determine the short-term E-modulus [13].

3.3 Microscopy

The internal structure of the compression-tested SCB is revealed by a high-resolution scan of a vertical cut through the specimen, obtained using a reflected-light scanner.

3.4 Life Cycle Assessment

A screening life cycle assessment (LCA) was conducted to evaluate the environmental impact of the SCB. The analysis focuses on the Global Warming Potential (GWP) as the main indicator, expressed in kg CO_2-equivalents (kg CO_2-eq). This indicator is particularly relevant for construction materials, as raw material extraction and manufacturing processes, especially binder production, contribute significantly to embodied emissions. The system boundary was defined as modules A1–3, including raw material supply, transport, and manufacturing. Environmental data were obtained from established databases [14, 15] and literature values where necessary [16].

4 Results

4.1 Compressive Strength and Modulus of Elasticity

Figure 3 presents the stress–strain behaviour of the SCB in comparison with that of pure wheat SB of different densities. The data for wheat SB with a bulk density of 106 kg/m^3 are taken from [5] and were obtained from small bales (31–36 cm height, 40–48 cm width, 30–120 cm length) tested in vertical orientation. The data for wheat SB with a bulk density of 140 kg/m^3, reported by [17], correspond to half bales measuring 120 cm × 120 cm × 90 cm (length × width × height) tested in horizontal orientation.

The shown stress-strain curve obtained from SCB specimens with a bulk density of 452 kg/m^3 shows an elastic response in the second portion of the curve (Phase II, Fig. 2). The slope of this segment yields a E-modulus of approximately 24.45 N/mm^2. By contrast, wheat SB with a bulk density of 140 kg/m^3 exhibit, according to the trend line, an estimated E-modulus of about 0.41 N/mm^2 within the deformation range shown, while bales with a density of 106 kg/m^3 reach approximately 0.33 N/mm^2 [5, 7]. Consequently, the SCB exhibits approximately sixtyfold higher stiffness than SB. After unloading, the specimens largely recovered their original shape, indicating externally elastic behaviour.

Moreover, the compressive strength of the SCB measured at a strain of 5% (0.86 N/mm^2) corresponds to approximately 4300% of the compressive strength of SB, which reach only about 0.02 N/mm^2 at the same strain level [5, 7]. Even when compared with compressive strengths of SB measured at strains exceeding 50% (0.45 N/mm^2), the SCB exhibits approximately 91% higher compressive strength [6].

4.2 Microscopy

A good homogeneity of the constituent materials is evident. No material nests of additives or lignin were observed. All specimen showed the compaction direction, which proceeds from top to bottom, giving rise to an anisotropic material behaviour. The limited compaction at the specimen edges becomes apparent, with the upper region displaying more loosening and voids than the lower region. No macroscopic cracks were detected within the specimen.

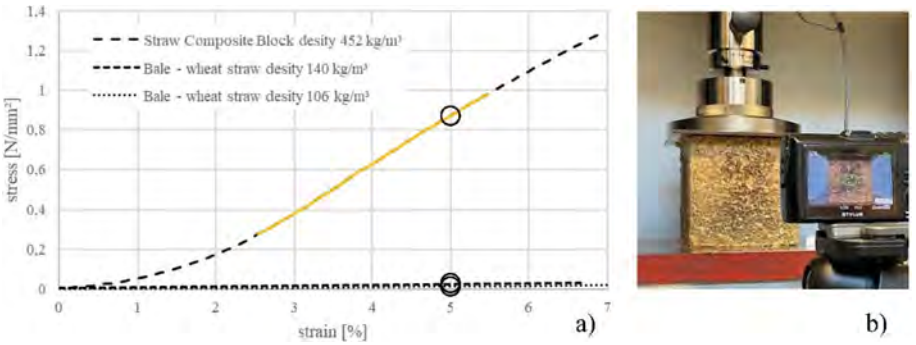


Fig. 3. a) Stress-strain curve of SCB (452 kg/m^3) compared with SB with densities of 106 and 140 kg/m^3 based on [5, 17], and b) SCB specimen in the testing setup [Photo: Katrin Linne].

4.3 Life Cycle Assessment

While SB with a density of 100 kg/m^3 exhibit a GWP of −129.4 kg CO_2-eq/m^3 [15]. SB with a density of 140 kg/m^3 can be assigned a GWP of − 181 kg CO_2-eq/m^3. Spruce shavings show an even lower GWP of −688.2 kg CO_2-eq/m^3 [14], which can be attributed to the longer growth period of spruce and the associated carbon storage during biomass formation. For 1 m^3 of SCB, 210 kg (42 wt.%) of spruce shavings are required, which therefore accounts for − 300.1 kg CO_2-eq/m^3. The same amount of straw (42 wt.%) accounts for − 271.7 kg CO_2-eq/m^3.

In contrast, kraft lignin exhibits the highest GWP within the observed materials, accounting to 0.6 kg CO_2-eq/m^3 [16]. For the SCB, approximately 20 kg/m^3 (4 wt.%) of lignin are required, corresponding to a GWP contribution of 12 kg CO_2-eq/m^3. When the contributions of the individual components are combined, the resulting GWP of the SCB amounts to −559.8 kg CO_2-eq/m^3. This represents an improvement of nearly 209% compared with the SB-GWP with a density of 140 kg/m^3. Effects of stabilisation, compaction and reduction of binder require further investigation.

5 Constructive Requirements: Shaping and Processing

The demoulded SCB exhibits a clearly defined geometry, enabling the production of precise masonry units and form bricks. After demoulding, the components can be easily trimmed using conventional woodworking tools. Unlike traditional SB construction, where the material is held in shape by binding straps, the straw composite possesses an internal bond that allows unrestricted cutting and shaping.

The SCB exhibits high dimensional stability, achieved through controlled compaction and thermal stabilisation. The combination of targeted compaction and lignin binding produces a homogeneous microstructure that retains its shape after curing and remains stable under typical temperature and moisture variations in building applications.

The density of the material can be adjusted by varying additive proportions and compaction. At about 500 kg/m^3, SCB is much lighter than conventional masonry materials, reducing transport and handling loads. It can be cut and drilled with standard timber

and masonry tools, producing clean edges without cracking. Its low density and homogeneous structure also facilitate post-processing. Surface treatments such as linseed oil varnish and Tadelakt have shown promising results in enhancing moisture protection and mechanical resistance.

6 Conclusion

This study introduced the Straw Composite Block (SCB) as a novel bio-based masonry material and investigated its mechanical behaviour in comparison with conventional SB construction with densities between 106 und 140 kg/m^3. The results demonstrate that the SCB exhibits substantially improved stiffness (↑ 5860%) and load-bearing capacity (↑ 4200%) at a strain of 5% while maintaining a comparatively low density (452 kg/m^3). In particular, the material shows an increase in stiffness of approximately sixtyfold relative to conventional SB, indicating its potential for structural use in low-rise construction.

Compared with traditional SB construction, the SCB enables the production of masonry units with precisely defined geometries and adjustable dimensions. The internal bonding of the composite material allows unrestricted cutting and shaping using conventional woodworking tools, facilitating processing and integration within standard masonry construction. At the same time, the comparatively low density of the material reduces structural loads and handling requirements during construction.

From an environmental perspective, calculations indicate that the SCB performs favourably, with an estimated GWP of −559.8 kg CO_2-eq/m^3, representing an improvement of approximately 209% compared with bales. Nevertheless, a comprehensive life-cycle assessment, including the influence of thermal stabilisation and compaction, is required to fully quantify the overall environmental impact.

While the results demonstrate promising mechanical properties, several aspects require further investigation, including optimisation of the mixture design, the influence of higher compaction levels, and long-term performance under varying environmental conditions. Future research should therefore address durability, moisture behaviour, and large-scale manufacturing processes.

Overall, the SCB combines low density, improved mechanical performance compared with SB construction, and good machinability, indicating its potential as a sustainable masonry material for low-rise buildings.

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Modelling Waste Flows in Mountain Huts to Support Circular Strategies: The Case Study of Rifugio Stoppani, Italy

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Abstract. Mountain huts face unique challenges in waste management due to their altitude, accessibility, and seasonal variability. However, quantitative data on waste generation in these contexts remain limited, hindering evidence-based decision-making. This study proposes a replicable methodology to quantify waste generation in mountain huts and to assess the feasibility of on-site recycling. The framework is applied to a one-year case study of Rifugio Stoppani, selected as a representative case study within the Italian Alpine Club hut classification system. The method combines unstructured interviews, structured collection of product-consumption data, and a workflow that models a typical year of hut attendance, enabling the reconstruction of annual waste flows by material. Results show that plastic and glass represent more than 75% of the total waste mass and that even relatively small quantities generate significant logistical burdens, requiring approximately 65 h of annual transport due to the absence of local collection systems. The study further evaluates the feasibility of on-site plastic recycling through low-scale injection moulding, demonstrating the potential to convert locally generated waste into functional objects and reduce transport effort by up to 83%. The proposed framework provides a transferable method for waste flow modelling in remote mountain infrastructures and supports the evaluation of localized circular economy strategies across the Italian Alpine Club hut network.

Keywords: Alpine Architecture · On-site Plastic Recycling · Circularity · Sustainable Built Environment · Waste Management · Off-grid Buildings

1 Introduction

Waste management in isolated mountain huts is structurally constrained by limited accessibility, seasonal operation, and the absence of on-site treatment infrastructure. In many Alpine contexts, residual waste must be transported downstream via helicopter or porterage, generating elevated logistical costs and additional environmental burdens [1, 2]. At the same time, mountain huts frequently constitute the primary permanent infrastructures in high-altitude areas and can represent significant localized sources of environmental

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pressure, particularly through solid waste and water use [3]. These impacts occur within ecologically fragile ecosystems increasingly affected by climate change, while the continued growth of mountain tourism intensifies material consumption and associated waste generation [4].

Despite growing attention to sustainability transitions in mountain regions, empirical quantification of waste generation at the scale of individual mountain huts remains limited and fragmented. Existing initiatives have predominantly focused on environmental behaviour [5] and awareness in mountainous areas rather than on modelling infrastructure-level material flows. Waste characterization studies in Alpine municipalities or along hiking routes provide useful information on typologies [6, 7], yet they do not capture the operational dynamics of huts, which involve seasonal peaks, supply pre-stocking, and limited storage capacity. Although European circular economy policies and initiatives [8, 9] promote local resource valorisation in mountain territories, implementation at hut scale remains limited, despite the potential to reduce transport requirements and material resupply in off-grid infrastructures. On-site transformation of waste represents a complementary strategy to traditional waste management practices that can bring environmental and social benefits to local communities [10, 11].

2 Methods

2.1 Workflow

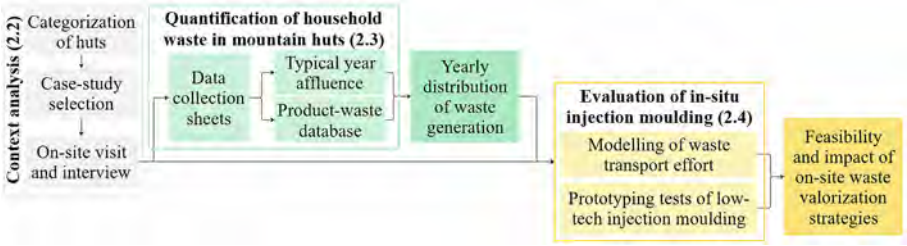


Fig. 1. Method workflow and structure of the work.

This study develops a replicable workflow (Fig. 1) to estimate annual waste generation in mountain huts by integrating product-level consumption data, attendance modelling, and material-specific waste factors. The approach is applied to a case study within the Italian Alpine Club (CAI) network, Rifugio Stoppani. The study also evaluates the on-site valorisation of plastic waste through small-scale injection moulding. Feasibility is assessed through prototyping tests and by estimating the potential reduction in waste transport. Comparing this scenario with conventional waste transport allows the evaluation of the environmental and social benefits of the strategy.

2.2 Context Definition and Analysis

Categorization of Mountain Huts and Method Reproducibility. Mountain huts differ substantially in accessibility and supply logistics, factors that directly influence material consumption and waste generation. To ensure methodological transferability, this study refers to the CAI classification system, which groups huts into five categories (A–E) based on accessibility (walking time or proximity to motorized or cableway transport) and supply modality (road, cableway, or helicopter) [12]. Huts within the same category share comparable logistical conditions and operational constraints. Positioning the case study within this framework allows the methodology to be replicated in huts with similar accessibility and supply characteristics.

Case Study Selection. Rifugio Stoppani (Fig. 2), located in the Lecco area of the Lombardy Prealps, was selected as the case study within the CAI classification framework. Categorized as a Class C hut due to its walking access time and supply modality, it keeps a strong functional connection with the nearby city of Lecco, serving as a destination for short excursions and weekend visits. The hut operates off-grid, it is not connected to municipal water, sewage, or waste-collection systems, requiring autonomous management of utilities and downstream transport of residual waste. The structure provides 22 sleeping places and a restaurant area with 45 seats. The hut is open throughout the year on weekends and selected weekdays, with peak attendance for Sunday lunches.

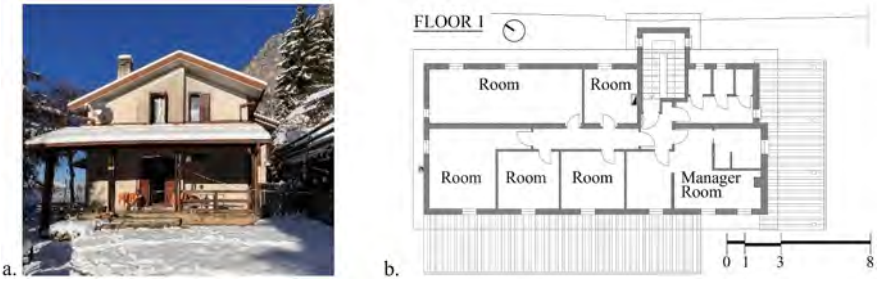


Fig. 2. a. Picture of the east side of Stoppani hut. **b.** First floor planimetry (authors)

On-Site Visit and Semi-structured Interviews. The methodology relies on semi-structured interviews and on-site visits to realistically assess the hut and its operator needs. This method was preferred to sensors/direct measurements as waste in mountain huts highly depends on weekday and seasonality. During the first on-site visit, a semi-structured interview was conducted with the mountain hut manager to investigate current waste management practices, with a specific focus on plastic waste streams. The interview addressed five main areas: (i) contextual characteristics of the hut, (ii) products and goods consumed in the hut (iii) existing waste management practices and related challenges, (iv) perceived feasibility of local processing and pre-processing of waste, (v) interest in locally manufactured goods from plastic waste.

2.3 Quantification Methodology for Household Waste in Mountain Huts

Data Collection Through Structured Consumption Sheets. The hut manager completes the Monthly consumption sheet and one Daily consumption sheet for representative typical days. The Monthly consumption sheet records products consumed monthly and the associated packaging waste. Quantities are reported separately for the peak-season months (May–June, September–November) and off-season months (December–March).

Products are grouped into 4 use categories: *Food*, *Cleaning*, *Sleeping* and *Heating*.

The *Daily consumption sheets* collect products directly related to the number of hut users (overnight guests, diners, or passing visitors). Waste generation throughout the year is estimated using the consumption categories: *Typical day* products (e.g., coffee, water, snacks) are reported as quantities consumed during a representative day; *Meal-related* products (e.g., butter, polenta, sausage) depend on the number of meals prepared, therefore the sheets collect the average number of meals served by type; goods purchased in bulk are classified under *Monthly* or *Yearly* consumption categories.

Development of Typical Year of Affluence at the Hut. To capture seasonal and daily variation in hut use, a typical year of attendance was constructed based on structured interviews with the hut manager, drawing on their operational experience and historical patterns. Three seasonal categories were defined: low (January, February, March, December), medium (April, July, August), high (May, September, October, November); along with typical daily attendance for each weekday in those seasons (Table 1). Given the strong influence of weather on visitor numbers, each day type was further differentiated into four conditions (clear, cloudy, rainy, heavy rain). The synthetic annual attendance profile was obtained by combining these attendance categories with daily meteorological data for 2024 from the Lecco, Via Sora weather station.

Table 1. Example of weighting the attendance according to weather

Period	Clear [n° people]	Cloudy: < 2 mm of cumulated rain/day [n° people]	Rainy: 2 mm < cumulated rain/day <10 mm [n° people]	Bad weather: >10 mm cumulated rain/day [n° people]
High season-weekdays	40	6	3	0
High season-weekends or events	60–70	6	3	0
High season special event	100	6	3	0

Development of Product-Waste Database. The interviews and consumption sheets results are reprocessed to create a database of products used in the huts and calculate the derived waste. Each product is listed together with the waste generated by its parts, its

mass, and material (Table 2). Most of the products packaging type is collected during the interview and through the data collection sheets; for items whose packaging types or details are missing, the waste-product database is completed by taking reference from other huts and referring to existing products found in Italian wholesale markets.

Table 2. Structure of waste-product database with percentage of use by guest.

Product	Category	% for 1 use	Waste from product	Material	Mass
Coffee	Food	1.000	Cup	PS	6.3 g
Coffee	Food	0.010	Cups packaging	LDPE	2.0 g
Coffee	Food	1.000	Coffee pod	PLA	3.0 g
Coffee	Food	0.020	Pod packaging	PI	1.0 g

As exemplified in Table 2, the database includes the use category of the product and all the wastes it produces, together with a percentage of the waste mass considered to be attributed to one use, defined in relation to the *Consumption category*.

Evaluation of In-Situ Injection Moulding of Plastic Waste. Waste generation data, combined with interviews on waste transportation practices, are used to evaluate on-site transformation as alternative waste valorisation strategy. The study focuses on plastic waste as proof of concept, testing on-site transformation of HDPE waste into small products through low-scale injection moulding. Being the hut not connected to the electrical grid and transport routes, production is carried out with a portable, knock-down, manually operated injection machine. The strategy is assessed by estimating the number of avoided waste transport. Interview data are used to model a typical waste transport scenario, including the number of bags transported, transport duration, and mode of transport.

Modelling Waste Transport Effort Through Interview Result. The monthly number of plastic waste bags generated is estimated using the bulk density (ρ_{bulk}) of loose-compacted plastic waste. Based on literature values [13, 14], a conservative average density of 35 kg m^{-3} is adopted. The hut uses 110 L trash bags (V), therefore the mass contained in each bag (m_{110L}) is modelled as in Eq. (1)

$$m_{110L} \approx \rho_{bulk}\ V \tag{1}$$

The monthly plastic waste mass generated is then divided by the mass contained in a single trash bag. The resulting value is rounded down to the nearest integer, and the leftover mass is considered added to the following month total. Finally, the calculated number of bags is compared with the values obtained from the interviews. According to the hut manager, plastic waste is periodically carried on foot from the hut to the nearest road-accessible mountain facility, where the accumulated bags are then transported by car to the municipal recycling centre in the valley. These operational practices were used to estimate the transport effort associated with waste management.

Prototyping Tests of Low-Tech Injection Moulding. The potential of local plastic recycling is assessed by quantifying the number of gadgets manufacturable from PS, LDPE, HDPE, PP, PLA, PET waste streams. The gadget, identified through stakeholder interviews, serves as a proof of concept, though the methodology can also be applied to small non-structural construction products. Then, the manufacturing process (Fig. 3) is tested on r-HDPE to verify feasibility and reliability. The selected gadget is a carabiner with a volume of 17 cm^3, digitally modelled in Rhino. The mould combines a slotted steel base mould with a 3D-printed insert, allowing interchangeable inserts for different products, thereby reducing tooling costs and material use. For HDPE, the process parameters are 190 °C melt temperature, 22 °C mould temperature, and 10 bar injection pressure, with 30 s injection, 1 min dwell, and 10 min cooling time.



Fig. 3. Modelling and manufacturing step of a carabiner from HDPE waste through low-tech injection mould and 3D-printed insert.

3 Results and Discussion

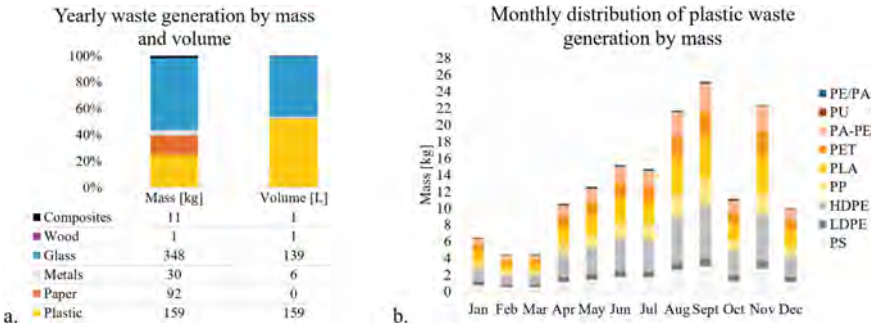


Fig. 4. **a.** Yearly household waste generation by mass and volume per waste material. **b.** Monthly distribution of plastic waste generation by mass per polymer type.

The annual waste generation (Fig. 4a) results show that plastic and glass represent the predominant waste fractions, with respectively 159 kg-158.9 L and 348 kg-139 L. Focusing on plastic materials, the monthly attendance chart (Fig. 4b) reveals a strong seasonal variability in hut usage, with a strong linkage between waste and seasonality.

The most consumed materials are HDPE and PLA, followed by PET, PP, and PA-PE. These results support the feasibility of implementing local recycling techniques, as most of the identified polymers, excluding PU, PA/PE, and PA-PE, have relatively low melting temperatures and established processing parameters for packaging grades.

The number of plastic waste bags, the travel time, and the number of manufacturable carabiners is presented in Table 3. Operational parameters related to waste collection and transport practices were derived from the semi-structured interviews with the hut manager.

Table 3. Results of the waste management strategy in terms of reduced travel time.

	Plastic waste [kg]	Waste bags [n°]	Travel time [h]	Gadgets [n°]	Leftover mass [kg]	Leftover bags [n°]	Reduced travel time [h]
Jan	6.48	1	2.17	31	0.94	0	0.00
Feb	4.48	1	2.17	21	0.66	0	0.00
Mar	4.52	2	3.33	21	0.67	0	0.00
Apr	10.55	2	3.33	52	1.54	0	0.00
May	12.59	4	6.67	63	1.81	1	2.17
Jun	15.19	3	4.50	76	2.18	1	2.17
Jul	14.71	4	6.67	74	2.10	0	0.00
Aug	21.69	6	9.00	110	3.08	1	2.17
Sept	25.17	6	9.00	128	3.56	1	2.17
Oct	11.12	3	4.50	55	1.62	0	0.00
Nov	22.41	6	9.00	113	3.16	1	2.17
Dec	9.95	3	4.50	49	1.42	0	0.00
Tot	**158.85**	**41**	**64.83**	**793**	**22.73**	**5**	**10.83**

The waste generation profile reflects both the operational characteristics of Rifugio Stoppani and the logistical constraints typical of mid-access Alpine huts. While glass constitutes the largest fraction by mass, plastic becomes the most relevant stream from a management perspective due to its volumetric contribution and association with catering activities. In infrastructure-limited environments where waste must be periodically transported downstream, storage capacity and transport frequency become critical parameters, making the volumetric behaviour of materials particularly relevant.

The seasonal distribution of plastic waste follows the attendance dynamics of the hut, with peaks during late summer and early autumn. This pattern is consistent with the hut's operational profile as a "city-connected" refuge serving a large share of day visitors and weekend users. As reported by the hut manager during interviews, most plastic waste originates from food packaging associated with meal preparation and supply storage, reflecting operational constraints typical of off-grid huts where food safety and storage stability limit bulk supply chains.

The modelling results indicate that the yearly plastic waste generation corresponds to approximately 41 trash bags, requiring an estimated 65 h of transport effort between the hut and the municipal recycling centre. Although the total material flow remains limited in absolute terms, the associated operational effort is significant due to the logistical isolation of the hut. Within this context, the evaluation of local valorisation strategies becomes relevant: the yearly plastic waste stream could enable the production of approximately 793 small, manufactured objects, reducing the plastic waste of 14% and reducing the travel time of 83%. These results illustrate the technical feasibility and impact of converting locally generated waste into functional products.

4 Conclusion

This study develops a replicable workflow to estimate waste generation in mountain huts by integrating product consumption data, attendance modelling, and product-specific waste factors. Applied to the case of Rifugio Stoppani, the method reconstructs annual waste generation patterns and identifies plastic and glass as the dominant fractions, accounting for over 75% of total waste by mass.

The results show that in off-grid infrastructures the relevance of waste streams cannot be assessed by mass alone, as volume and transport logistics strongly influence management practices. Even relatively small waste quantities generate frequent transport operations: in the case study, waste removal requires about 65 h of travel per year due to the absence of on-site treatment infrastructure. The hut therefore represents a typical remote context where on-site waste transformation could reduce environmental and logistical burdens by limiting transport needs and time, while simultaneously acting as a visible circular practice that can increase visitors' awareness.

By linking waste quantification with operational constraints, the proposed framework supports the evaluation of localized circular strategies. A proof-of-concept assessment of low-tech injection moulding demonstrates the potential to transform locally generated plastic waste into small functional objects, showing how material valorisation and volume reduction could decrease transport effort by up to 83%. The methodology is designed to be transferable across the CAI network and to support decision-making on waste management in remote mountain infrastructures.

The main limitation of the study lies in its application to a single case study. Future research could extend the data collection methodology to different categories of huts and informal settlements. In addition, current validation relies primarily on interviews with hut managers; these insights could be complemented by direct measurements to improve the accuracy of total waste mass estimates.

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Physical and Mechanical Properties of Geopolymer Mortars Produced with Different Bacterial Strains within a Circular Economy Framework

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Abstract. This study investigates the physical and mechanical performance of metakaolin–slag-based geopolymer mortars containing ureolytic bacteria, such as *Sporosarcina pasteurii*, and cave-derived bacteria, including *Bacillus safensis* and *Micrococcus aloeverae*, with a view toward exploring their self-healing potential. The incorporation of microbial healing in geopolymer systems aligns with circular economy principles by valorizing industrial by-products, enhancing material durability, and reducing the need for resource-intensive repairs. While laboratory strains like *Sporosarcina pasteurii* are well-known for their high urease activity and alkaline tolerance, cave-isolated strains offer distinct advantages due to their natural adaptation to high-alkalinity and nutrient-poor geological environments, providing resilient and highly compatible ureolytic alternatives. The formation of natural cave structures, including stalactites, stalagmites, cave pearls, and flowstones, demonstrates the efficacy of microbially induced carbonate precipitation for sustainable concrete repair. In this study, the workability, physical properties (water absorption, open porosity, bulk density, ultrasonic pulse velocity, shrinkage), and mechanical properties (compressive and flexural strength) of the mortars were evaluated. The results are expected to introduce novel cave-derived microbial species to the literature and promote the use of environmentally sustainable, self-healing construction materials that contribute to a circular and resource-efficient building sector.

Keywords: Geopolymer · Metakaolin–Slag-Based Geopolymer Mortar · *Bacillus safensis* · *Micrococcus aloeverae* · Sustainable Construction Materials · Circular Economy

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1 Introduction

The global construction industry faces the dual challenge of increasing infrastructure demand and the need for environmental sustainability. Traditional cement production contributes approximately 5% of global CO_2 emissions, motivating the search for eco-friendly alternatives [1]. Geopolymers, introduced by Davidovits in 1978, are alkali-activated aluminosilicate materials formed from industrial by-products such as fly ash and slag or processed natural materials like metakaolin. These materials develop a three-dimensional Si–O–Al–O network, offering enhanced mechanical performance, durability, and a lower carbon footprint compared to ordinary Portland cement [2, 3].

Despite these advantages, geopolymer composites are susceptible to crack formation, which compromises durability by increasing permeability and allowing the ingress of aggressive agents. While conventional repair methods can address larger cracks, micro-cracks (< 0.3 mm) remain challenging to treat, highlighting the need for innovative self-healing strategies [4–7].

Microbially induced carbonate precipitation (MICP) offers a promising autonomous healing mechanism. In this process, microorganisms precipitate calcium carbonate ($CaCO_3$) within cracks, sealing them and reducing permeability. Although *Sporosarcina pasteurii* exhibits high alkaline tolerance, standard laboratory strains may encounter physiological limitations in geopolymers, prompting the use of resilient cave-isolated strains adapted to extreme geological environments [6, 8, 9].

Cave environments are natural analogs for $CaCO_3$ precipitation, producing speleothems like stalactites and stalagmites. Microorganisms from these environments are hypothesized to offer superior survival and biomineralization capabilities within geopolymer matrices. Integrating these cave-derived bacteria with metakaolin–slag-based geopolymers provides a novel approach to enhancing mechanical performance, durability, and autogenous self-healing, while promoting environmentally sustainable construction [10].

Cave-derived bacterial isolates used in this study were obtained from soil and surface samples collected during fieldwork carried out at Yarık Sinkhole (Antalya, Türkiye). Prior to this study, these isolates had been screened for their biomineralization and carbonate precipitation potential under laboratory conditions.

This study evaluates the fresh and hardened properties of geopolymer mortars incorporating three bacterial strains—*S. pasteurii, Bacillus safensis,* and *Micrococcus aloeverae*. Their survival in the highly alkaline geopolymer environment and their ability to induce MICP were assessed. The findings aim to identify the most suitable bacterial strains for sustainable crack-healing applications and to expand knowledge on cave-derived microorganisms for eco-friendly, self-healing construction materials. Previous studies have shown that these cave-derived isolates exhibit carbonate precipitation and biomineralization activity in B4 calcification medium. These findings suggest that these bacteria could be suitable candidates for self-healing geopolymer applications. The performance of the selected strains is planned to be compared, and their crack-healing potential will be experimentally verified, particularly for *Micrococcus aloeverae*, whose MICP activity is less documented in the literature.

2 Materials and Methods

2.1 Materials

The main pozzolanic binder in the geopolymer was metakaolin with high pozzolanic activity ($SiO_2 + Al_2O_3 > 85\%$) and a specific gravity of 2.52 g/cm^3, conforming to ASTM C618, Class N, with a Blaine fineness of 20 000 cm^2/g [11, 12]. Ground granulated blast furnace slag (GGBFS) was also used as a pozzolan, with a specific gravity of 2.91 g/cm^3, conforming to ASTM C989, Class R, and a Blaine >2750 cm^2/g [13, 14]. The high Blaine values of both materials indicate fine particle sizes, promoting rapid reaction and early strength development. As the alkaline reactant mixture a combination of laboratory-prepared sodium hydroxide (NaOH) solution and commercially available sodium silicate (Na_2SiO_3) solution was used. The NaOH solution was prepared 24 h prior to mortar production at a concentration of 12 M by dissolving 99.0% purity NaOH pellets [15] in distilled water [16], considering the molar mass of NaOH as 40 g/mol. The 40% sodium silicate solution [17] had a SiO_2/Na_2O molar ratio of 2.70 and a density of 1.37 g/cm^3.

In the geopolymer mortars, river sand was used as the aggregate, with a maximum particle size of 2.0 mm [18]. Polyvinyl alcohol (PVA) fibers (density: 1.1 g/cm^3) were incorporated at 0.60% by volume into all mixtures to enhance ductility and crack-bridging performance.

The bacterial strains used in this study were the reference ureolytic strain *Sporosarcina pasteurii* (SP) and two cave-derived isolates, *Bacillus safensis* (Y109) and *Micrococcus aloeverae* (Y147). The Y109 and Y147 strains used in this study were previously isolated from Yarık Düdeni in Antalya. Isolation was achieved using culture-based microbiological methods from soil and surface samples during cave exploration expeditions. The obtained isolates were purified and identified by 16S rRNA gene sequencing. These strains were selected based on prior screening studies demonstrating their carbonate precipitation and biomineralization activity on B4 calcification medium, which suggested their potential suitability for self-healing geopolymer applications. Before impregnation, bacterial suspensions were adjusted to McFarland 3 turbidity standard (approximately 9×10^8 CFU/mL) so that all series were prepared at a comparable cell density. To ensure a reliable comparison, all three strains were evaluated based on their ureolytic activity; therefore, suspensions were prepared in B4 medium supplemented with urea to support and trigger urease-mediated carbonate precipitation, rather than standard PBS. GGBFS was used as the bacterial carrier material in the impregnation process.

2.2 Methods

Initially, preliminary experimental studies were conducted to determine the most suitable solid binder system. Geopolymer mortars based on 100% GGBFS, 75% GGBFS + 25% metakaolin, and 25% GGBFS +75% metakaolin were produced and mechanically evaluated. The mortar series exhibiting the highest performance was selected for further investigation. For the selected mortar series, fresh geopolymer samples were examined in terms of workability [20], while their physical properties, including water absorption,

open porosity, and bulk density [21], ultrasonic pulse velocity [22], and shrinkage [23], as well as their mechanical properties, namely compressive strength [24] and flexural strength [25], were evaluated. The specimens used for testing were cured at ambient temperature (20 ± 2 °C).

The bacterial impregnation procedure was adapted from Ziada (2022) [19], with GGBFS substituted as the carrier material. Isolate selection was based on prior screening studies in which both strains demonstrated crystal formation and carbonate-precipitation activity on the B4 calcification medium. Bacterial cells were weighed into centrifuge tubes and suspended in B4. The resulting suspension was then mixed with GGBFS to initiate bacterial immobilization onto the slag surface. The mixture was incubated at 30 °C for 24 h, after which it was filtered to yield a bacterial-impregnated GGBFS paste. To reduce excess moisture, the paste was oven-dried at 30 °C for 40 min prior to use. For experiments evaluating physical and mechanical properties, 9.9 mL of bacterial suspension, 47 mL of B4 solution, and 44 g of slag were used in the impregnation process.

3 Results and Discussion

3.1 Preliminary Findings

Initially, fiber selection was carried out using 100% slag-based geopolymer mortars. Within this scope, carbon fibers, basalt fibers, and PVA fibers were tested at volume fractions of 0.4%, 0.6%, and 0.8%. Based on the workability (flow table test) and flexural tensile strength results, a PVA fiber content of 0.6% was selected for further experiments. Subsequently, partial replacement of slag with metakaolin was applied to obtain more balanced geopolymer composites. In GGBFS-based geopolymer systems, rapid reaction kinetics may lead to variations in workability and microstructural development due to the high reactivity of slag. In contrast, metakaolin provides a more controlled aluminosilicate source, contributing to a more stable geopolymerization process and improved microstructural homogeneity. Therefore, GGBFS–metakaolin-based systems are expected to exhibit more consistent and reproducible performance. Based on preliminary screening results, the mixture containing 25% GGBFS and 75% metakaolin (Mix 3), which exhibited the highest 1-day compressive strength (46.6 MPa) among the tested mixtures (Mix 1: 23.8 MPa; Mix 2: 29.4 MPa), was selected as the primary binder composition for the main experimental program (Table 1). The compressive strength results were obtained from three 5 cm cube specimens prepared for each mixture. Prior to testing, the specimens were subjected to oven curing at 80 °C for 24 h.

Table 1. Components and strengths of geopolymer mortars (for 375 cm^3 specimens).

Mix ID	Components (g)					
	GGBFS	Metakaolin	NaOH	Na_2SiO_3	Sand	PVA
Mix 1	200	0	61.3	122.7	500	2.5
Mix 2	150	50	61.3	122.7	500	2.5

(*continued*)

Table 1. (*continued*)

Mix ID	Components (g)					
	GGBFS	Metakaolin	NaOH	Na_2SiO_3	Sand	PVA
Mix 3	50	150	61.3	122.7	500	2.5

3.2 Main Experiments

Table 2 presents the design of the investigated mixtures, including mix proportions and bacterial incorporation details.

Table 2. Mix design and bacterial incorporation details (for 1499.3 cm^3 specimens).

Series ID	Bacterial type	Components (g)						
		GGBFS	Bio-GGBFS	Metakaolin	NaOH	Na_2SiO_3	Sand	PVA
GP-SP	SP	156	44	600	245.3	490.7	2000	9.9
GP-Y109	Y109	156	44	600	245.3	490.7	2000	9.9
GP-Y147	Y147	156	44	600	245.3	490.7	2000	9.9

According to the flow table test results, the highest flow value was obtained for the GP-Y147 series (132.3 mm), followed by the GP-Y109 (125.3 mm) and GP-SP (119.3 mm) series. This suggests that different bacterial strains may have a slight influence on workability.

Figure 1 shows the appearance of the geopolymer mortar specimens produced within the scope of this study immediately after being cast into molds.



Fig. 1. Geopolymer mortar specimens produced within the scope of this study.

The geopolymer mortars showed minor variations in water absorption (11.3–11.7%), open porosity (21.4–22.1%), and bulk density (1.88–1.89 g/cm^3) across the bacterial series, indicating a negligible effect of bacterial strains on their physical properties.

The UPV test results obtained on 28-day-old geopolymer mortar specimens showed slight variations among the different bacterial series. The UPV values ranged from 3284 m/s to 3400 m/s. The highest UPV value was recorded for the GP-Y147 series (3400 m/s), followed by the GP-SP series (3371 m/s), while the lowest value was obtained for the Mix-Y109 series (3284 m/s). Overall, the results indicate that the incorporation

of different bacterial strains had a minor influence on the ultrasonic pulse velocity of the hardened geopolymer mortars.

Overall, a consistent relationship was observed between the physical properties (water absorption, open porosity, and bulk density) and the ultrasonic pulse velocity (UPV) results. The GP-Y147 series, which exhibited the lowest water absorption (11.3%) and open porosity (21.4%) together with the highest bulk density (~1.89 g/cm^3), correspondingly showed the highest UPV value (3400 m/s). In contrast, the Mix-Y109 series, which presented relatively higher porosity and water absorption values, exhibited the lowest UPV (3284 m/s), while the GP-SP series remained intermediate in all measured properties. These findings confirm that lower porosity and water absorption are associated with higher ultrasonic wave propagation velocity, indicating a coherent microstructure–wave transmission relationship in the hardened geopolymer mortars.

The differences observed among the bacterial series may reflect the distinct physiological and biomineralization characteristics of the tested strains. Earlier work on Yarık Sinkhole isolates has shown that these bacteria are capable of inducing carbonate precipitation under controlled laboratory conditions. Against this background, the higher mechanical performance of GP-SP and GP-Y109 is linked to favorable bacterial–matrix interactions. Although all strains exhibit ureolytic activity, their geopolymer performance differed. The lower strength in GP-Y147 is attributed to its non-spore-forming nature, as resistant *Sporosarcina* and *Bacillus* endospores withstand the high pH of geopolymerization, whereas non-spore-forming *Micrococcus* cells are more vulnerable to such harsh conditions, leading to reduced biomineralization within the matrix.

Shrinkage measurements were conducted for the GP-SP and GP-Y109 series. Considering the specific properties of geopolymer mortars, measurements were taken at days 1, 2, 3, 4, 5, 6, 7, 14, and 28. This sampling scheme allowed for a detailed assessment of both early-age and later-age shrinkage behavior. The results indicate that both GP-SP and GP-Y109 geopolymer mortar series exhibited progressive shrinkage with curing time. In general, shrinkage increased continuously up to 28 days for both mixtures, reaching final values of −2.3% for both GP-SP and GP-Y109, indicating similar long-term volumetric behavior. In the early curing stage (1–7 days), both series showed fluctuations in shrinkage development. GP-Y109 generally exhibited slightly higher shrinkage at very early ages, while GP-SP showed a more pronounced shrinkage development in the later early-age period. However, after 14 days, both mixtures demonstrated nearly identical shrinkage trends, suggesting that the influence of bacterial incorporation on deformation behavior is limited. Overall, the results indicate that both bacterial series exhibit similar drying and autogenous shrinkage behavior, with only minor differences between GP-SP and GP-Y109 throughout the curing period.

The compressive and flexural strength results of the 28-day-old geopolymer mortar specimens show a clear variation among the different bacterial series. The GP-SP series exhibited the highest compressive strength (52.5 MPa), followed closely by the GP-Y109 series (50.4 MPa), while the GP-Y147 series showed a noticeably lower compressive strength (37.0 MPa). This indicates that the bacterial strain has a more pronounced influence on compressive strength compared to flexural strength. In contrast, flexural strength values were relatively close to each other, ranging from 8.7 MPa to 9.1 MPa. The GP-SP series again showed the highest flexural strength (9.1 MPa), while the lowest

value was observed for the GP-Y147 series (8.7 MPa). Overall, the results suggest that bacterial incorporation has a limited effect on flexural performance, whereas compressive strength is more sensitive to the type of bacterial strain used, with GP-Y147 exhibiting a significantly lower structural performance compared to GP-SP and GP-Y109.

Across all tested properties, the geopolymer mortars demonstrated consistent performance regardless of bacterial incorporation. While physical properties remained largely unaffected, mechanical performance—particularly compressive strength—showed a strain-dependent response. Overall ranking of performance can be summarized as: GP-SP $\approx$ GP-Y109 $>$ GP-Y147 These results suggest that cave-derived bacterial strains such as *Bacillus safensis* and *Micrococcus aloeverae* can perform comparably to *S. pasteurii* in geopolymer systems. This supports their potential use as sustainable microbial agents in self-healing cementitious materials.

4 Conclusion

In this study, the fresh and hardened properties of metakaolin–slag-based geopolymer mortars incorporating *S. pasteurii* (SP), *Bacillus safensis* (Y109), and *Micrococcus aloeverae* (Y147) were investigated. All mixtures exhibited adequate workability and similar physical properties, including water absorption, open porosity, and bulk density, indicating a generally compact and homogeneous microstructure. Compressive strength was clearly influenced by bacterial strain, with GP-SP and GP-Y109 outperforming GP-Y147, while flexural strength showed only minor differences among the series. Overall, the performance ranking can be summarized as GP-SP $\approx$ GP-Y109 $>$ GP-Y147. These results demonstrate that cave-derived bacterial strains can perform comparably to conventional ureolytic bacteria in geopolymer mortars. The findings support the potential use of alternative biomineralization-positive microorganisms for sustainable, self-healing construction materials. Future work will focus on investigating the autogenous self-healing potential of metakaolin–slag-based geopolymer mortars activated via an injection-based bacterial delivery method.

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Integrating Circular Economy and Fire Safety: The Need for Updated EU Regulation

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Abstract. The integration of circular economy principles in construction is transforming material use, building design, and waste management across Europe. Reuse, recycling, and resource efficiency are increasingly prioritized to reduce environmental impacts and support sustainable development. However, the adoption of circular practices introduces new challenges for fire safety. Many reused or recycled materials may be combustible, emit toxic smoke, or behave unpredictably under fire conditions, creating risks for occupants and emergency responders. The recent revision of the EU Construction Products Regulation (CPR) emphasizes enhanced transparency, performance documentation, and traceability of construction products, providing an opportunity to align circular construction strategies with fire safety requirements. This paper highlights the critical need to investigate how circular practices—such as the use of reclaimed components, recycled polymers, and bio-based materials—affect fire performance. It also addresses regulatory gaps, testing needs, and certification pathways required to safely implement circular materials. Performance-based fire safety approaches, combined with harmonized European standards, are essential to ensure that circular building strategies do not compromise safety. Strengthening the connection between circular economy principles and the CPR will enable safer, more sustainable buildings while supporting Europe's climate and resource-efficiency goals. Digital building logbook (DBL) harmonization, with included building fire safety performances data, is the proposed as solution for this gap.

Keywords: Circular Economy · Fire Safety · Construction materials · EU Regulation · Sustainable Construction

1 Introduction

The population growth, resources deficiency, climate change impact and increasing natural hazards are recognized challenges in societies all over the world. In the same time, technology is rapidly advancing; people are concentrating in cities, the need for housing expands. Sustainability concept is widely acknowledged.

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The circular economy is focused on the recovery and reintegration of materials into the value creation process, which also offers sustainable added value. Materials used in construction can be leased, reused, recycled or reused in other ways. These processes help to reduce the environmental impact and offer sustainable added value, as the production of building materials accounts for around 60% of the total energy requirement in the building's life cycle.

Greenhouse gas emissions from material extraction, manufacturing of construction products, construction and renovation of buildings are estimated at 5–12% of total national GHG emissions. Greater material efficiency could save 80% of those emissions [1]. Circularity and sustainability must be incorporated in all stages of a value chain to achieve a fully circular economy: from design to production and all the way to the consumer.

Sustainability of buildings is typically rated based on measuring carbon footprint from their entire lifecycle, but a disruptive event like a fire is not included in those calculations. Furthermore, the effects of a fire go beyond the immediate building and content, the victims, and emergency response personnel. Fire adds pollutants to the air, contaminates surrounding soil and water systems, and impacts the health of citizens. It is, therefore, unfortunate that, when looking at sustainability concepts and policy measures, there is no clear link to fire safety. At the same time, 90% of all fire victims are killed by fires in buildings [2]. Fire safety concepts for the use of reused building materials are still to be developed.

Fires in buildings are now more prominent, more unpredictable, and more dangerous than ever before: they impact society, the environment and the economy. The World Health Organization (WHO) estimates global burn deaths at 180 000 annually, the vast majority of these in low and middle-income countries, with fewer fire safety regulations or provisions [3]. The situation in developed countries is troubling as well. Within Europe, more than 3500 people are killed annually in fires based on a five-year average [4]. The number of injuries is approximately 20 times the number of fatalities, resulting in at least 70 000 injuries per year in the EU alone. The losses in the USA are similar in absolute terms [5].

This paper gives a short insight into recent policy documents and scientific papers on fire safety in the circular economy in buildings. The regulation improvement proposal includes digital and smart tools to ensure sustainability and safety monitoring of buildings during the whole buildings' life-cycle.

2 Policy Documents on Circular Economy

In 1983, the United Nations launched the World Commission on Environment and Development which resulted in a global document addressing sustainability in 1987, called "Our Common Future" [6]. The World Commission was dissolved when their seminal report was issued, but the work started in 1983 continued, leading to Agenda 21 in 1992 [7], and Agenda 2030 in 2016 [8]. Achievements of Sustainable development goals 11 and 12: *Make cities and human settlements inclusive, safe, resilient and sustainable* and *Ensure sustainable consumption and production patterns* are measured by,

among others, targets addressing adequate, safe and affordable housing and basic services, inclusive and sustainable urbanization, resource efficiency, mitigation and adaptation to climate change, resilience to disasters and reduction waste generation through prevention, reduction, recycling and reuse.

The European Green Deal [9], launched in 2019, is the EU's comprehensive growth strategy launched in 2019 to transform Europe into a climate-neutral continent by 2050. It aims to cut greenhouse gas emissions by at least 55% by 2030 (relative to 1990) and reach 90% reduction by 2040. It focuses on sustainability, cleaner energy, transport, and a circular economy.

A new Circular Economy Action plan from 2020 [10] sets down seven key areas essential to achieving a circular economy: plastics; textiles; e-waste; food, water and nutrients; packaging; batteries and vehicles; buildings and construction. The aim is to make construction and demolition more sustainable, promoting the use of recyclable and sustainable building materials.

The Renovation Wave Initiative [11], launched in 2020, aims to renovate 35 million buildings by 2030, at least to double the annual renovation rate of buildings in the EU, to reduce emissions, enhance energy efficiency and to improve the resilience of buildings.

A new comprehensive Strategy for a Sustainable Built Environment [12] will ensure coherence across the relevant policy areas such as climate, energy and resource efficiency, management of construction and demolition waste, accessibility, digitalization and skills. It will promote circularity principles throughout the lifecycle of buildings, among other, by addressing the sustainability performance of construction products in the context of the revision of the Construction Product Regulation [13], including the possible introduction of recycled content requirements for certain construction products, taking into account their safety and functionality, including fire safety, as one of the basic requirements. The two general objectives of the CPR revision are to (1) achieve a well-functioning single market for construction products and to (2) contribute to the objectives of the green and digital transition, particularly the modern, resource-efficient and competitive economy.

Circularity and access to materials is one of the main elements of the latest core EU Commission Policy Initiative – Clean Industrial Deal (2025–2030) [14], which includes an adoption of a circular economy act in 2026 to accelerate the circular transition and ensure that scarce materials are used and reused efficiently, reduce our global dependencies and create high-quality jobs. The aim is to have 24% of materials circular by 2030.

Looking beyond 2030, the co-legislators have recently agreed on a 2040 climate target [15], of 90% net reduction in greenhouse gas emissions compared to 1990 levels in order to put the EU on a firm path to climate neutrality by 2050. It points out how circular business models can create significant reductions in greenhouse gas emissions in hard-to-abate sectors, such as the built environment [16].

3 Fire Safety and Sustainability

The Fire Safety or impact of fire on human population, environment, climate and economy is not addressed as specific issue in above mentioned documents; it might be included in urban resilience, although it mainly considers disaster risk resilience.

In response to the need for fire research globally, the Association for Fire Safety Science (IAFSS) has produced the Agenda 2030 [17], for a fire safe world to highlight fire research needs that address two identified societal grand challenges – (1) climate change, resilience and sustainability and (2) population growth, urbanization and globalization. Fire Safety and Sustainability is recognized as one of seven Fire Science and Engineering fields of research and action.

In the European Union there are about 5,000 fire deaths per year with many more individuals suffering injuries and permanent scars. More than 90% of fires occur in homes and almost all are preventable. Based on statistics, scientific research and the opinion of over 300 experts, the European Fire Safety Alliance proposed the European Fire Safety Action Plan [18], and identified five focus areas with 12 actions outlined, where major progress can be made in reducing the number of fires, deaths and injuries in Europe. Focus area 3 is devoted to developing knowledge and competency to ensure Fire Safety to become an inseparable part of the Energy Transition, including electrification and sustainable and circular construction.

Meacham and McNamee [19, 20], identified gaps in implementation of both sustainable and fire safe attributes into buildings and set recommendations for future research work, including: integration of sustainable attributes into fire incident reporting systems, more robust and appropriate test methods for assessment of material, components and system performance, advanced risk and performance assessment methods and tools (e.g. digitalization, BIM) and to bring the sustainability and safety communities together to better understand the challenges each faces and find solutions together. The literature study indicates that while fire hazards and risks, which have previously been identified, have been addressed in many regards, fire safety is still considered relatively late in the design process and does not always carry through to the operational phase of a building. Inclusion of fire safety in the early stages of product and system development, and in building or community planning and design, would help to alleviate many fire safety issues before they truly emerge, e.g. questions of material fire performance, system design, and first responder accessibility.

There are several obstructions that can be relevant regarding fire safety requirements associated with reused products [21]. Various building materials such as recycled concrete can be used without hesitation and contribute to achieving climate targets, but prefabricated concrete components, steel structures or modular timber components must be considered separately in terms of fire safety. Many materials, such as pipes, are not suitable for reuse in terms of fire safety or cost-effectiveness.

Changes in requirements over time highlight the need to know the age of the product or material in question, the historical development of the building code, and how previous requirements can be compared to the current ones. Fire performance determination of product aimed for reuse can be done either by knowing the fire performance based on historic testing data if this is still applicable (depending on the previous use, condition and the age of element) or through assessment.

Resilience ensures that buildings can withstand and recover from fire events, retaining their functionality; sustainability ensures that fire safety measures are environmentally, economically, and socially viable over the building's lifecycle; and smartness enables

the deployment of advanced technologies, considering human and institutional coordination to enhance both resilience and sustainability [22]. The goals of resilience and sustainability in building fire safety are aligned. Sustainable buildings should not be prone to burning, whereas building fire resilience ultimately contributes to sustainability. Fire safety planners must therefore work with the authorities to develop concepts for the use of reused building materials. This includes the evaluation and documentation of the materials as well as compliance with safety standards and fire safety classifications. Above all – regarding the fire safe use of circular materials in both renovation and new construction projects – the primary demand is a risk informed decision making, to ensure benefits from circularity.

4 Digital Building Logbook Connecting Fire Safety and CE

The European Commission defined a Digital Building Logbook (DBL) [23] as a common repository for all relevant building data, starting from the design phase, which plays a fundamental role in information management. DBL should be a collector of building-related data: by gathering and organizing data related to a building, can serve multiple purposes, such as enhancing building efficiency, supporting maintenance strategies, managing technical aspects, ensuring safety, and preserving economic value. It can include administrative documents, plans, description of the land, the building and its surrounding, technical systems, traceability and characteristics of construction materials, performance data such as lifecycle emissions, as well as links to building ratings and certificates. As a result, it also enables circularity in the built environment.

Fire safety data (Fire Safety Plan; evacuation plans, signalization, alarms etc.) are recognized [23] in an indicative selection of data fields structured according to eight information categories: administrative, general, building descriptions, operation and maintenance, building performance, material inventory, smart readiness and finance, based on existing initiatives in 2020, but there are no records of fire safety data in report on 40 existing building logbook initiatives and six H2020 research projects analyzed [24].

Fire safety performance of construction products should also be included in DBL data, ranked according to CPR. Consistencies with fire safety legislative frameworks need to be addressed and updated in case of regulatory changes. Sustainability should be one of the key topics to be addressed under a construction specific approach compatible with the delivery of information by manufacturers, but focused on building assessment according to the reference European methodology Level(s).

The building fire risk assessment and fire safety measures, both passive and active, evacuation plans and building resilience to fire, are of crucial importance for human lives and sustainability of our built environment. Building digital logbook is an effective and efficient contemporary tool for informed decision making for all of us.

5 Conclusions

Fire safety is demanded in many applications where combustible materials such as plastics, composites, fibers or wood are increasingly used. The safety of recycled building materials in the event of fire is an important issue, which has not been sufficiently taken into consideration so far.

Fire safety planners must therefore work with the authorities to develop concepts for the use of reused building materials. This includes the evaluation and documentation of the materials as well as compliance with safety standards and fire safety classifications. Fire scientists and engineers globally should foster multidisciplinary collaboration, develop new models, methods, data and education, to raise awareness of the role of fire safety science and engineering in building and infrastructure design, construction, and management.

A digital building logbook, as a common repository for building information, can include a group of informative attributes of and documents for a building that have to be collected during its lifecycle and that can be linked to BIM, tracking changes, and updates. Static data as well as real-time data obtained from Internet of Things devices can be incorporated; data integration will contribute to the regular updates of buildings. The most important action to engage is to achieve harmonization of digital building logbook at European level, which is quite a challenge, since, so far, countries are developing their own version of DBL according to the national specific rules and regulations.

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The Potential of Non-Destructive Testing for Determining Structural Steel Mechanical Properties for Reusing Applications

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Abstract. Structural steel reusing is becoming a key strategy to promote the sustainable construction practices and to reduce the environmental footprint associated with steel production. However, the broad deployment of steel reuse is currently limited by the need to assess mechanical properties such as yield and tensile strength, ductility, and toughness. Traditionally, these properties are determined through destructive testing methods, such as tensile and Charpy impact tests, which are time-consuming and require damaging the steel components. Current guidelines, including CEN/TS 1090-1:2024, provide methods for assessing reclaimed steel by relying on hardness and chemical testing, supplemented by provenance data (e.g., construction date, beam profile, and documentation) to find representative test members for destructive validation. Beyond these standards, recent advancements in non-destructive testing (NDT) offer a promising alternative. Growing evidence supports the ability to indirectly estimate mechanical properties by analyzing the metallurgical, acoustic, and electromagnetic characteristics of steel. This paper presents a review of various NDT techniques, including ultrasonic testing, electromagnetic methods (such as eddy current and Barkhausen noise analysis), portable hardness testing, spectroscopy, and optical microscopy. Each technique is discussed in terms of its principles, sensitivity to metallurgical features, and potential for practical implementation. The advantages and limitations of these methods are compared, ultimately providing a decision framework for field applicability to obtain usable estimations of structural steel mechanical properties in various reuse scenarios.

Keywords: Structural steel reuse · Non-destructive testing · Sustainable construction · Mechanical properties assessment

1 Introduction

For steel reuse to be practical on a large scale, we need a fast, affordable, and safe way to check the quality and properties of old steel structural elements. One of the biggest challenges in reusing steel is making sure it is strong, durable, and safe enough for

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new projects. This requires accurately determining the steel's mechanical properties and subsequently steel grades, which has traditionally been done using destructive testing methods. Destructive testing has always been the common and standardized method for checking the mechanical properties of steel. Techniques like tensile testing and impact testing involve cutting samples from steel products and testing them until they break. While these methods are effective, they are expensive, time-consuming, and destroy the steel being tested. This makes destructive testing unsuitable for steel reuse since it wastes the material.

To overcome these problems, non-destructive testing (NDT) methods could offer a faster, cheaper, and more efficient alternative. NDT allows us to evaluate the steel without causing any damage. Techniques like hardness measurement, optical microscopy, chemical analysis, electromagnetic methods (ET), and ultrasonic testing (UT) can be used to predict the mechanical properties of steel while keeping it intact. This makes NDT an ideal method for testing steel that will be reused, as it maintains the material and reduces both time and costs.

2 Optical Microscopy and Chemical Composition Analysis as the Primary ND Methods

It is known that the mechanical properties of steel products depend primarily on chemical composition and microstructure. Therefore, considering these two aspects can lead to the assessment of the steel mechanical properties. Optical microscopy and chemical spectroscopy can be considered non-destructive approaches when metallography and spectroscopy are performed on the surface of the beam without damaging or cutting it. While in non-destructive microscopy and spectroscopy surface preparation does require grinding and polishing using portable devices, the extent of material removal is acceptable as long as the grinding depth remains within the cross-sectional deviation limits specified in EN 10034.

Strengthening mechanisms can be understood as the hindrance of dislocation movement by crystallographic defects, which create obstacles, such as precipitates, solute atoms (substitutional or interstitial), grain boundaries, or other dislocations, that distort the path of dislocations. Accordingly, approaches to increase the strength of steel include: (1) refining the grain size, (2) solid-solution strengthening, (3) precipitation strengthening, (4) phase transformation (e.g., quenching and tempering, or rapid cooling), and 5-increasing dislocation density through work hardening.

The chemical composition of steel undoubtedly plays a crucial role in all strengthening mechanisms. When it comes to grain size refinement, certain alloying elements can inhibit grain growth by forming precipitates that hinder grain boundary movement (Zener pinning), or by solute atoms sticking to the boundaries and drag on them (Solute drag mechanisms) during grain growth. In ferritic-pearlitic steels, alloying elements further enhance strength through solid solution and precipitation hardening mechanisms. Additionally, they influence hardenability and, consequently, have an impact on the nature of phase transformation. Although the contents of alloying elements can be identified using non-destructive chemical spectroscopy, this approach alone does not reveal the extent or manner in which they contribute to strengthening. Nevertheless, knowing the

steel chemical composition provides valuable insights. It allows the determination of carbon equivalent for weldability assessment, estimation of pearlite content in ferritic-pearlitic steels based on carbon content, classification of non-alloyed versus alloyed steels according to EN 10020, and verification of compliance with the requirements of the relevant product standard as indicated in CEN/TS 1090-201:2024.

Given the influence of grain size on the mechanical properties of steel, the correlation between grain size and certain mechanical properties is commonly expressed through Hall-Petch form Eqs. (1), (2) and (3), [1, 2]. These equations describe a linear relationship between mechanical properties and the inverse square root of grain size.

Over years of research, the original Hall-Petch Eq. (1), developed for yield strength assessment, has been extended to incorporate the effects of solid-solution strengthening, precipitation, and dislocation density. This expanded formulation thus accounts for the primary strengthening mechanisms in structural steels [3].

$$\sigma_y(\text{yield strength}) = \sigma_0 + \mathrm{K}_y \times \mathrm{d}^{-\frac{1}{2}} \tag{1}$$

$$\sigma_f(\text{cleavage fracture stress}) = \mathrm{K}_f \times \mathrm{d}^{-\frac{1}{2}} \tag{2}$$

$$\mathrm{T}_B(\text{ductile to brittle transition temperature}) = \mathrm{T}_0 - \mathrm{K}_B \times \mathrm{d}^{-\frac{1}{2}} \tag{3}$$

Where $\mathrm{K_y}$, $\mathrm{K_f}$, $\mathrm{K_B}$, are the Hall-Petch slope and d is the mean grain size [2]; σ_0 is the friction stress of a pure iron single crystal which can be estimated around 70 MPa for steel [1].

3 Non-destructive Hardness as the Most Known Method in Structural Steel Mechanical Assessment

Hardness is the primary non-destructive technique referenced in guidelines for reusing structural steel products. CEN/TS 1090-201 recommends hardness testing for estimating ultimate tensile strength (UTS) and for comparing the mechanical properties of members within a test unit. Numerous studies have also investigated the correlation between hardness and steel mechanical properties [4, 5]. ISO 18265 provides a conversion table for deriving UTS from hardness values across different steel grades, though it notes that these converted values are approximate and cannot replace direct tensile testing.

The relationship between hardness and yield or ultimate strength in steel is grounded in empirical research. Cahoon et al. proposed equations correlating tensile and yield strength with hardness, incorporating both hardness values and the strain-hardening exponent [4, 5].

Several studies indicate a linear correlation between hardness and yield strength, tensile strength, and even elongation across a range of steel grades [4, 6]. For instance, one study suggests that yield and tensile strength can be estimated using the following equations:

$$\text{Yield Strength} = -90.7 + 2.876 \times \mathrm{HV} \tag{4}$$

$$\text{Tensile Strength} = -99.8 + 3.734 \times \text{HV} \tag{5}$$

where HV is the Vickers hardness value. This relationship results in a good enough coefficient of determination, 0.9212 for yield strength and 0.9347 for ultimate tensile strength, indicating its predictive capability [4].

4 Ultrasonic Test (UT) Methods for Steel Products Properties Assessment

This method is based on transmitting high frequency sound (ultrasound) into the material and evaluate the changes in the received feedback sound and correlate the change to the steel mechanical properties. In this paper, talking about different UT methods is not possible, and just limited it to introducing the UT parameters.

There are four main UT parameters used for materials properties characterization:

Ultrasonic Velocity: The speed of sound in solid materials depends on density and elastic properties [7]. In solids, density along with elastic constants such as Young's modulus, shear modulus, and Poisson's ratio are functions of ultrasonic velocity [7]. Different microstructural phases in steel exhibit varying densities; consequently, the volume fraction of these phases influences ultrasound velocity. This parameter can therefore be exploited to assess variations in microstructural phases and, in turn, the mechanical properties of structural steel. Ultrasound velocity has been used to estimate yield strength, ultimate tensile strength, and elongation in low-carbon hot-rolled steel [8], as well as hardness [9] and different microscopic phases in carbon steel [10].

Ultrasonic Attenuation: The loss of energy occurs in ultrasound as it travels through a material is known as attenuation [11]. This parameter consists of two components: absorption and scattering. Absorption arises from mechanisms such as dislocation damping, hysteresis losses, and thermoelastic effects, among others. Scattering, depending on the ultrasound wavelength, is primarily governed by microscopic features that disrupt wave propagation, including grain boundaries, phase interfaces, and microscopic discontinuities such as porosities and microcracks [11]. Attenuation has been utilized for grain size measurement [9, 12], yield strength estimation in plain carbon steel [12], and fracture toughness assessment [13].

Backscatter Amplitude: The scattering component of attenuation can provide more detailed microstructural information when scattered waves are monitored and separated from the primary ultrasound signal. This parameter has valuable applications, including the assessment of grain size and second-phase size distribution [14].

Spectral Analysis: The fast Fourier transform is used to convert the ultrasonic time-amplitude signal into the frequency domain, yielding a frequency-amplitude spectrum. The frequency spectrum provides valuable information about steel microstructure and can therefore be employed for assessing mechanical properties. Among the features derived from this spectrum, peak frequency and bandwidth are commonly used for material characterization [11]. This approach has been applied to grain size and yield strength assessment [15].

5 Electromagnetic (ET) NDT Techniques for Steel Products Properties Assessment

Among non-destructive methods, electromagnetic (ET) techniques are unique in their widespread use for characterizing ferromagnetic materials properties. Unlike paramagnetic and diamagnetic materials, the magnetization of ferromagnetic materials is nonlinear, resulting in a hysteresis loop upon completion of a full magnetization cycle. This loop can be parameterized into key values that are utilized in ET methods for the nondestructive assessment of steel mechanical properties. The electromagnetic properties of steels can be parametrized in five values listed below with a short description and the ND methods measuring them:

Coercivity (Hc): Hc is defined as the intensity of the external magnetic field required to reduce the magnetization of a material to zero. This parameter can be estimated nondestructively using methods such as incremental permeability, Barkhausen noise, and tangential field techniques [16]. Coercivity has been used to assess a wide range of material properties, including grain size [17], pearlite fraction [18, 19], hardness [17, 20], yield strength [20], ultimate tensile strength [20], elongation [20], and chemical composition [20].

Magnetic Saturation (Bs): This parameter is the state at which an increase in the external magnetic field no longer results in a corresponding increase in the magnetization of the material. Bs can be approximated using incremental permeability and tangential field methods [16]. This parameter has been utilized to assess grain size [19], carbon and ferrite content [19], hardness [19, 20], yield strength [20], ultimate tensile strength [20], and elongation [20].

Remanence (Br): Remanence is the residual magnetization remaining in a material after the external magnetic field has been removed. Br can be approximated using incremental permeability and tangential field methods [16]. This parameter has primarily been used for carbon content assessment [18] and has seen less frequent application than other magnetic parameters for steel characterization.

Permeability (μ): Magnetic permeability is the measure of a material's ability to support the formation of a magnetic field within itself. This parameter can be approximated using incremental permeability, eddy current, and tangential field methods [16]. Permeability has been exploited to assess carbon content [18, 20], yield strength [20], ultimate tensile strength [20], elongation [20], and hardness [20].

Magnetic Barkhausen Noise (MBN): On a microscopic scale, magnetization is not a perfectly smooth process. Rapid, discrete changes in magnetic domain alignment generate stochastic voltage pulses known as magnetic Barkhausen noise (MBN). This parameter is measured using the MBN method [16], which is one of the most effective approaches for steel property characterization [17, 21, 22]. MBN has been utilized to assess grain size [17, 21], pearlite content [22], carbon content [22], hardness [17], yield strength [21], and ultimate tensile strength.

6 Comparative Evaluation and Selection Framework for Non-destructive Tests Methods

Selecting the most reliable NDT method for assessing the streel products' mechanical properties requires a direct comparison of these techniques for this specific application, which is outlined below.

From a metallurgical perspective, the combination of optical microscopy and chemical composition analysis appears to be the most reliable method. However, optical microscopy has insufficient resolution to distinguish phases in accelerated cooled microstructures, such as tempered martensite, upper and lower bainite, or to observe fine microscopic details like precipitates. Consequently, this approach is of limited utility for quenched and tempered (QT) steels, and lacks accuracy for steels where precipitates play a significant role. In addition, they can be performed non-destructively only on the accessible surface of a steel product; hence, they are not applicable to steel products where the microstructure varies across the thickness.

Moreover, this reliability comes at a high cost. The process requires grinding, polishing and etching which are time consuming and skill dependent. Extracting microscopic features is also challenging; it is either performed manually by expert operators, which is labor-intensive, or through computer vision methods. The latter requires a robust model that remains undeveloped for low quality images obtained from portable devices outside laboratory settings.

Hardness measurement is a well-established method for assessing the ultimate tensile strength and comparing steel products mechanical properties. However, it can yield inaccurate estimates for steel products with varying microstructure across the thickness. Steels undergone accelerated cooling and self-tempering exhibit a harder surface compared to their core and subsurface. Obviously, for such steels, tensile properties estimated from hardness measurements are higher than the actual values.

In contrast, electromagnetic (ET) and ultrasonic (UT) testing methods can interrogate both the subsurface and bulk of the steel, not just the surface. This provides more comprehensive microstructural information and enables better prediction of mechanical properties when the steel type is unknown. However, their application in property assessment is still under investigation, and comprehensive research is needed to evaluate their ability to predict the mechanical properties of structural steel.

When comparing ET and UT, several factors emerge:

Depth of Penetration: UT can scan nearly the entire depth of a steel section, whereas ET penetration is limited by the skin effect to a maximum of approximately 4 mm, depending on the technique and frequency used.

Couplant Dependency: The reliability of many ultrasonic methods, particularly amplitude based measurements, depends strongly on couplant conditions. This creates challenges for practical applications where uniform coupling cannot be reliably ensured.

Geometric Requirements: Most UT methods also require accurate thickness measurement, which needs access to both sides of the beam flange or web. However, surface ultrasonic methods, such as Rayleigh waves, or parameters like frequency spectra, can be used when access is restricted.

Operational Advantages: ET methods do not require a couplant and can even be applied over thin coatings. ET is also more widely employed than UT for assessing surface and subsurface steel properties.

7 Conclusions

An overview of non-destructive methods for assessing steel mechanical properties was conducted, including their applicability and drawbacks. While the combination of optical microscopy and chemical spectroscopy offers reliable prediction based on metallurgical theories, it is expensive and unsuitable for testing accelerated cooled steel products. Hardness testing, governed by ISO 18265, is a well-established method for evaluating ultimate tensile strength. However, it is not applicable when the steel type is unknown and may involve products where the microstructure varies across the thickness. To address the challenge of assessing the properties of steel products with varying microstructure across the thickness, ultrasonic and electromagnetic testing methods are recommended for further investigation for such application. These techniques have been successfully used to evaluate the mechanical properties of steels, as they are sensitive to key microstructural features such as grain size and microstructure type, and are not limited to surface characterization.

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Evaluation of Mechanical and Physical Properties of Medium Density Fiberboard Bonded with Bio-Based Adhesive

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Abstract. This study investigates the performance of a novel bio-based adhesive for use in wood-based panel manufacturing. The adhesive, formulated from functionalized lignin and urea-formaldehyde (LUF), was used in medium density fiberboard. Two LUF adhesive formulations containing functionalized lignin at 40 wt.% and 50 wt.%, based on the amount of urea, were synthesized. The MDF panels are produced on an industrial scale with a thickness of 18 mm. Mechanical properties including modulus of rupture (MOR), modulus of elasticity (MOE), and internal bonding strength (IB) as well as physical properties such as density, water absorption (WA), thickness swelling (TS), surface roughness and free formaldehyde emission of the samples, were determined. Overall, the properties of LUF-bonded MDF panels were enhanced compared to those of UF-bonded MDF panels. The results indicate that LUF adhesives demonstrate promising mechanical and physical performance and have the potential to serve as a sustainable alternative to conventional adhesives in wood-based panel applications.

Keywords: Bio-based Adhesive · Lignin · MDF · Mechanical and Physical Properties

1 Introduction

Urea formaldehyde resins are the most prevalent adhesives in the wood-based panel industry, including applications for plywood, particleboard, and medium density fiberboard (MDF) [1]. Their economic competitiveness, rapid curing rates, and robust adhesion characteristics contribute to their widespread use [2]. Despite their advantages, UF resins are constrained by two primary limitations: the emission of formaldehyde and inadequate moisture resistance [3]. In response to environmental and health concerns associated with formaldehyde-based resins used in wood-based panels, growing research attention has been directed toward the development of bio-based adhesives derived from renewable resources, such as lignin, tannins, and starch, for applications in MDF production [4]. Lignin is a complex and highly branched aromatic polymer that represents the second most abundant natural biopolymer in lignocellulosic biomass after cellulose. It

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is estimated that roughly 50–70 million tons of lignin are generated annually from pulping and biorefinery processes, yet more than 98% of this lignin is typically combusted for low-value energy recovery rather than valorized into high-value materials [5–7]. Owing to its renewability, aromatic structure, and high natural abundance, lignin has emerged as a promising sustainable feedstock for bio-based adhesive systems, offering an eco-friendly alternative to conventional petroleum-derived resins such as PF and UF adhesives [8, 9]. However, the industrial application of native lignin is often hindered by its structural heterogeneity and low chemical reactivity [10]. In addition, despite its many advantageous properties, the structural heterogeneity of lignin and its relatively low reactivity compared to petroleum-derived phenolic compounds pose significant challenges. Therefore, current research has focused on various modification methods, optimized resin formulations, and lignin functionalization to enhance its effectiveness in industrial adhesive applications [11].

The inherent low reactivity of native lignin presents a significant challenge for its direct application as a wood adhesive [12]. To overcome this, functionalization methods are employed to introduce or enhance reactive sites. Ultrasonic processing represents a physical functionalization technique that can disrupt the lignin structure, increase its surface area and expose more hydroxyl groups for reaction [13]. This mechanical activation can facilitate subsequent chemical modifications or improve miscibility with other adhesive components. Mineral additives can further enhance lignin's functional properties. These additives can act as catalysts, cross-linking agents, or reinforcing fillers, improving the overall performance of lignin-based adhesives.

In this study, lignin was functionalized in an ultrasonic bath with mineral additives. The resulting functionalized lignin was incorporated into UF adhesive formulations at levels corresponding to 40%, and 50% of the total urea content, and the effects of these additions on the physicochemical properties of the adhesive were evaluated using various methods. Subsequently, the prepared modified UF adhesives were applied in the production of MDF panels, and the mechanical, physical and surface properties of the panels were evaluated in order to contribute to the development of formaldehyde-free, eco-friendly wood composites that meet both industrial performance requirements and environmental safety standards.

2 Materials and Methods

2.1 LUF Adhesive Production and MDF Panel Manufacture

In the study, an acidic lignosulfonate was employed as the adhesive component in the study. The lignosulfonate solution was functionalized in an ultrasonic bath in the presence of mineral-based additives (FL). After the drying process, the FL solution was kept in the reactor under continuous stirring until it was used in adhesive production. LUF adhesive was produced in the adhesive plant using the FL solution under the same procedure with standard UF adhesive production process at solid content of 50%. The FL solution was incorporated into the adhesive system at the final stage of the reaction in an amount corresponding to 40% and 50% of the total urea content on a solid FL basis. A total of 12 t of LUF adhesive were produced, which consisting of 8 t with 40% Flignin and 4 t with 50% f-lignin solids.

The MDF production was carried out at Vezirköprü Forest Products Co. (*Peli Parke)*, Türkiye. Hardwood fibers (85%) and softwood fibers (15%) were used as raw materials in this study. The MDF panels were manufactured on the production line under 140–145 mm/s at 18 mm panel thickness. A total 54 m^3 of the produced panels were trimmed. Prior to testing, the panels were pre-conditioned at 25 °C and 65% relative humidity until they reached equilibrium moisture content.

2.2 FTIR Characterization of LUF Resin

FTIR spectra of LUF adhesives were recorded using a PerkinElmer Spectrum Two FT-IR spectrophotometer equipped with an ATR accessory to identify the functional groups present in the adhesive samples. The spectra were collected in the wavenumber range of 4000–400 cm^{-1}

2.3 Mechanical and Physical Testing Methods of MDF Panels

The modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond strength (IB) of the fiberboard panels were determined in accordance with the EN 310 [14] and EN 319 [15] standards using a universal testing machine (Imal IB600, Imal S.r.l., Italy). Water absorption (WA) and thickness swelling (TS) of panel specimens were determined after 24 h of immersion in distilled water, following the EN 317 [16] standard. WA and TS were calculated by comparing the measurements of the water-conditioned specimens with those of the initial dry samples. Ten replicates were evaluated for each type of fiberboard.

The formaldehyde emission values were measured in accordance with EN 120 [17]. The surface roughness of the samples was determined using a Mitutoyo Surftest SJ-310 device in accordance with ISO 4287:1997 [18] Surface Texture Standard. Color measurements were conducted using a Konica Minolta CM2600D colorimeter. In addition, the data were statistically analyzed using analysis of variance (ANOVA) and Duncan's mean separation tests.

3 Results and Discussion

3.1 Characterization of LUF Adhesives

The physicochemical properties of LUF adhesives prepared with 40% and 50% lignin ratios were investigated using FTIR-ATR analysis.

As the lignin content increases, the pH decreases slightly from 8.15 to 7.81, likely due to lignin's phenolic and mildly acidic nature. The adhesive's viscosity increased from 37 s to 49 s, indicating increased intermolecular interactions with LUF glue and the formation of a more compact internal structure. Because lignin has a larger and more complex structure, it increases hydrogen bonding and interactions in the UF resin, leading to higher viscosity. The solids content remained essentially unchanged (52.15% to 52.3%), suggesting that the incorporation of lignin did not lead to a measurable change in the total solids. The two types LUF adhesives had a uniform brown color, typical of lignin-infused materials, affirming lignin's effective blending into the adhesive.

Table 1 shows that the two adhesives exhibited highly similar FTIR spectra, confirming that the core UF polymer structure remained intact despite the increased lignin content.

Table 1. Comparative FT-IR peak assignments of LUF adhesives.

Wavenumber (cm^{-1})		Functional Group	Assignment
40%	50%		
3341	3339	O–H stretching/N–H stretching	Broad band attributed to hydroxyl groups from lignin phenols and N–H groups of urea structures in the adhesive network
2968	2970	C–H stretching (aliphatic	Asymmetric stretching of $–CH_2$ and $–CH_3$ groups, mainly from methylene bridges formed during UF polymerization
1628	1627	C=O stretching (amide I)/aromatic C=C	Characteristic amide carbonyl vibration of urea–formaldehyde structures, also overlapping with aromatic skeletal vibrations of lignin
1548	1549	N–H bending (amide II)	Amide II band related to N–H deformation and C–N stretching in UF resin structure
1464	1463	CH_2 bending	Deformation vibration of methylene bridges ($–CH_2–$) linking the UF polymer network
1387	1385	C–N stretching/CH_3 bending	Associated with methylol groups and C–N bonds in the UF adhesive structure
1255	1256	C–O stretching (phenolic/ether)	Phenolic C–O vibration from lignin units and ether linkages formed during condensation reactions
1136	1142	C–O–C stretching	Ether linkages and alcohol groups within the lignin-modified adhesive matrix
1011	1013	C–O–C stretching	Secondary alcohol or ether groups from lignin and methylol groups
777	777	Aromatic C–H out- Aromatic C–H out-of-plane bending of-plane bending	Characteristic vibration of substituted aromatic rings present in lignin

Small peak shifts have been observed in some spectral regions, with the broad absorption band around 3340 cm^{-1} shifting slightly towards lower wavenumbers. This is thought to be due to increased hydrogen bonding associated with higher lignin content. Small changes in the C–O–C and C–O vibrational regions (1250–1000 cm^{-1}) are due to the increased presence of lignin derivative ether and phenolic moieties within the adhesive matrix. In addition, the appearing of lignin peak at 906 cm^{-1} can be explained in the 50% FLignin sample indicates a more significant involvement of lignin-derived aromatic structures. Increasing the lignin content has a minimal effect on the structural integrity of the UF polymer network, while primarily acting on lignin-specific functional groups.

UF resins form a cross-linked polymer network characterized by methylene (-CH_2) and methylene ether (-CH_2–O–CH_2-) linkages, generated through the methylolation and subsequent condensation of urea with formaldehyde. Added immediately after the final urea addition, FLignin integrates into the UF polymer network via phenolic and aliphatic hydroxyl groups, thereby enhancing intermolecular hydrogen bonding interactions and enabling the incorporation of lignin-derived aromatic functional groups into the adhesive matrix. Consequently, the UF polymer backbone remains intact while being reinforced by lignin-derived functional groups, resulting in the formation of the LUF adhesive.

FT-IR analysis revealed that incorporation of mineral-modified FLignin at levels up to 50% maintained the fundamental chemical structure of the UF adhesive, without inducing significant structural alterations.

3.2 Mechanical and Physical Properties of the MDF Samples

The mechanical and physical properties of the MDF samples and their homogeneity subsets are indicated in Table 2. Statistical analysis test results noted that there are statistically significant differences between the average values of the mechanical properties of the MDF samples bonded with standard and lignin based UF adhesives. All test samples have met minimum required values for EN322-1 standard [19].

Functionalized lignin based urea formaldehyde adhesive increased MOR corresponding to dry weight ratio of lignin. The highest MOR and MOE values was recorded for LUF50 samples at 34.98 MPa and 3997.13 MPa, respectively. Increasing lignin content at a high level in the LUF resin resulted in a stiffer surface of the MDF panel with ultrasonic functionalization and mineral additives by mitigating low-reactive groups in lignin. Gendron et al. [20] noted their studies that the isolated lignin had more reactive hydroxyl groups and higher surface area than native lignin this led superior adhesive performance for wood based panel production.

The internal bonding test is showing the significant indicator for determining adhesive performance in wood based panels. The IB values of the samples bonding with LUF had higher than those of standard UF, which was enhanced by approximately 22–30% compared to the samples bonding with standard UF. Functionalized process of lignin enhanced the internal bonding by increasing cross-linking and reactivity of lignin [21, 22]. The IB values of LUF based samples met and exceeded the minimum requirement of 0.55 MPa by EN 322-1 standard.

The water absorption (WA) and thickness swelling (TS) values and statistical test results were presented in Table 2. The WA and TS test results demonstrated a significant

Table 2. Mechanical and physical properties and their homogeneity groups of the MDF samples.

ID	MOR (MPa)	MOE (MPa)	IB (MPa)	WA (%)	TS (%)
Standard UF	30.55 (c)* 1.71**	3344.00 (c) 94.56	0.58 (b) 0.08	11.77 (c) 0.81	36.79 (b) 0.63
LUF 40	3.73 (b) 0.88	3490.05 (b) 102.09	0.72 (a) 0.03	8.85 (ab) 0.49	30.68 (a) 1.66
LUF50	34.98 (a) 1.09	3997.13 (a) 31.92	0.67 (a) 0.04	8.07 (a) 1.16	31.39 (a) 1.44
EN 322-1	20	2200	0.55	N/A	12

*Homogeneity groups based on Duncan's Multiple Range Test. The letters refer significant differences at the $P < 0.0001$ level. ** standard deviation

enhancement in dimensional stability, the similar the improvements observed in the mechanical properties of the LUF-bonded MDF samples. The improvements in the WA and the TS of the LUF bonded samples were achieved by 31.4% and 16.6%, respectively compared to standard UF bonded MDF. This is related to functionalization process of, mineral additive during LUF synthesis, led to increase surface area, and reactive hydroxyl groups resulted the hydrophobicity of the resin [20, 23]. These findings were supported by Gumowska & Kowaluk [4] and Boran et al. [24]. Additionally, LUF40 and LUF50 MDF panel groups met the EN 322-1 standard, which requires a maximum thickness swelling of 12% after 24 h of water immersion.

3.3 Surface Properties of the MDF Samples

The surface roughness of MDF panels was evaluated using the Ra, Rq, and Rz parameters. Panels bonded with standard UF adhesive exhibited the highest roughness, indicating a relatively uneven surface profile. The partial substitution of UF resin with lignin in LUF40 panels led to a modest decrease in surface roughness (Ra = 4.038 μm, Rq = 5.129 μm, Rz = 25.127 μm), suggesting that the incorporation of lignin improves resin flow and fiber bonding uniformity during hot pressing. This effect became more pronounced in LUF50 panels, which exhibited the lowest roughness values (Ra = 2.896 μm, Rq = 3.868 μm, Rz = 20.469 μm), indicating a significantly smoother surface compared to both the control and LUF40 panels. The observed reduction in surface roughness with increasing lignin content can be attributed to the viscoelastic properties and higher molecular weight of lignin, which enhance adhesive distribution and reduce fiber lifting on the panel surface during pressing.

3.4 Formaldehyde Emission of MDF Panels

The free formaldehyde contents of the MDF panels were evaluated according to the E1 emission limit (<8 mg/100 g) for wood-based panels. The control panel bonded with conventional UF adhesive exhibited a formaldehyde content of 16 mg/100 g, which

is significantly higher than the E1 threshold and therefore does not comply with the required emission class.

In contrast, the panels manufactured with LUF adhesives showed a noticeable reduction in formaldehyde content. The LUF40 (7.02 mg/100 g) and LUF50 (6.95 mg/100 g) were clearly below the limit value. These results indicate that increasing lignin substitution in the adhesive formulation effectively reduces free formaldehyde content and enables compliance with the E1 emission class. Values above this limit are classified as E2 emission class (EN 13986) [25]. The reduction in formaldehyde emission can be attributed to the chemical structure of lignin, which contains phenolic hydroxyl groups capable of reacting with free formaldehyde and forming methylene bridges. As a result, lignin can act as a formaldehyde scavenger, decreasing the amount of free formaldehyde released from UF-based adhesives. Similar findings have been reported in previous studies, where partial substitution of UF resin with lignin significantly reduced formaldehyde emission in wood-based panels [26, 27].

4 Conclusions

In this study, functionalized lignin in the presence of mineral additives was synthesized via an ultrasonic-assisted method to form a novel lignin-urea- formaldehyde adhesive. The performance of LUF resin was measured in industrial-scale MDF panel production. In conclusion, the panel samples bonded LUF at incorporation of 40 and 50% Flignin wt.% into urea have yielded sufficient mechanical and physical properties. In the light of these findings, the novel bio-adhesive provides a sustainable alternative to petroleum-based wood binders.

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Recycled Textile Waste as a Circular Material for Efficient Acoustic and Thermal Treatment

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Abstract. Traditional acoustic and thermal insulation materials often rely on energy-intensive manufacturing and non-renewable resources, contributing to environmental degradation. Integrating circular materials into building applications can reduce landfill waste, lower embodied carbon and improve resource efficiency. In alignment with circular economy principles, this study investigates the acoustic and thermal performance of recycled textile waste used as a treatment material.

The intrinsic sound absorption behaviour was first characterized in the laboratory using an impedance tube to determine the normal-incidence sound absorption coefficient of small-scale specimens. To assess real-world performance, complementary measurements were carried out in a classroom with suboptimal acoustic conditions, where the textile was applied on wall-mounted panels and selected ceiling zones. Reverberation time (RT) was measured before and after treatment, while clarity (C50 and C80) and speech transmission index (STI) were derived to quantify the effect on speech intelligibility and overall acoustic comfort. Laboratory and in-situ results demonstrated consistent improvements in acoustic performance, confirming that recycled textile waste provides effective absorption to support reverberation control and enhance speech-related metrics.

In parallel, the thermal behaviour of the textile was evaluated under controlled laboratory conditions. The thermal conductivity coefficient was determined using a Heat Flow Meter (HFM), yielding an average value of $\lambda \approx 0.039$ W/m·K, indicative of good thermal insulation capability.

Owing to its porous fibrous structure, availability and environmental advantages, recycled textile waste emerges as a circular and potentially resource-efficient material for acoustic and thermal treatment in building applications.

Keywords: Recycled textile · Acoustic treatment · Reverberation time · Thermal insulation · Sound absorption

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1 Introduction

Environmental pollution has intensified in recent decades, driven by rapid population growth, urbanisation and technological development [1]. Increasing volumes of wastewater, air emissions and solid waste are placing growing pressure on ecosystems, degrading environmental quality and threatening biodiversity and human health. As production and consumption continue to expand, effective waste management and valorisation have become central challenges in the transition toward a circular and resource-efficient economy.

This challenge is particularly evident in the textile sector, one of the most resource-intensive and environmentally impactful industries. In the European Union (EU), approximately 12.6 million tonnes of textile waste are generated annually, of which clothing and footwear account for around 5.2 million tonnes. Despite this volume, only about 22% of post-consumer textile waste is separately collected for reuse or recycling, while the majority is incinerated or landfilled [2]. These practices result in significant material losses and environmental burdens, highlighting the urgent and growing need to move beyond the linear consumption model.

In response, textile-waste policy in the European Union has increasingly evolved toward binding regulatory measures. Since 1 January 2025, Member States have been required to set up separate collection for textiles under the Waste Framework Directive, as amended by Directive (EU) 2018/851 [3]. This was strengthened by Directive (EU) 2025/1892, adopted on 10 September 2025, which introduces mandatory extended producer responsibility (EPR) for textile and textile-related products [4]. Under the revised rules, Member States must ensure that the EPR schemes are established by 17 April 2028 [4].

Within this context, the construction sector offers significant potential for the valorisation of textile waste [5–7]. Conventional acoustic and thermal insulation materials are often associated with high embodied energy and reliance on non-renewable resources [8]. Integrating recycled materials into building applications can reduce environmental impacts while improving resource efficiency [9]. Recycled textile waste, characterised by a porous fibrous structure, exhibits promising properties for both sound absorption and thermal insulation [10–12]. However, existing studies rarely provide a combined assessment of the acoustic and thermal performance of recycled textile materials across both laboratory and in-situ conditions. Furthermore, the composition of domestic waste streams varies across regions, potentially influencing material properties and necessitating context-specific investigation.

This study investigates the potential of recycled textile waste for acoustic and thermal applications in buildings through a set of complementary evaluations. The same recycled textile material was examined under different test configurations: laboratory sound absorption measurements, in-situ classroom acoustic application and laboratory thermal conductivity testing. Accordingly, the study provides an integrated assessment of the material's potential, while recognising that the reported acoustic and thermal results were obtained for different thicknesses and installation conditions.

By evaluating laboratory-scale material properties and in-situ performance, the research aims to contribute to the development of building materials with potential

relevance to circular economy and resource-efficiency goals. Economic and life-cycle aspects are beyond the scope of the present study and require further investigation.

2 Materials and Methods

2.1 Recycled Textile

The investigated material was a nonwoven felt (Fig. 1), produced from recycled textile waste sourced from the domestic textile industry [13]. It consisted predominantly of polyethylene fibers and contained approximately 7% polyester, which acted as a thermally activated binder during heat treatment, thereby promoting fiber interlocking and ensuring structural integrity without the use of additional chemical binders.



Fig. 1. Recycled textile.

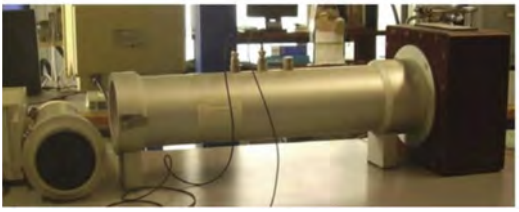


Fig. 2. Two-microphone impedance tube used for sound absorption measurements.

2.2 Impedance Tube Measurement of Sound Absorption

Normal incidence sound absorption coefficients were determined using the transfer-function method in accordance with ISO 10534-2 [14]. Measurements were performed with a two-microphone impedance tube (Fig. 2), where plane waves were generated by a loudspeaker at one end and the specimen was mounted at the opposite end under rigid backing conditions. The tube had an internal diameter of 100 mm, corresponding to an upper frequency limit of approximately 2000 Hz. The tested samples had a thickness of 35 mm (6 layers) and a bulk density of ~50 kg/m^3.

2.3 In-Situ Classroom Acoustic Assessment

An in-situ acoustic assessment was performed in a rectangular classroom with dimensions of 6.7 m × 13.8 m × 3.3 m. Recycled textile material, supplied as a pre-manufactured nonwoven felt produced from recycled textile waste, with a thickness of 3–6 mm and a bulk density of 40–50 kg/m^3 was placed around existing plywood panels (Fig. 3a, b), as well as on additional wall surfaces and within every third span between the ceiling ribs (Fig. 3a). The textile was mechanically fixed to the supporting surfaces using pins. The total textile area used was approximately 80 m^2. No additional treatment was applied prior to installation, the material was only cut to the required

dimensions. The intervention aimed to assess the in-situ acoustic performance of the recycled textile, without consideration of aesthetic constraints.

In building acoustics, the suitability of spaces for speech and music is usually evaluated using acoustic parameters such as reverberation time (RT), clarity indices (C50 for speech and C80 for music) and the speech transmission index (STI). Reverberation time measurements were carried out using a Cirrus CR:171B Class 1 sound level meter and loudspeaker emitting pink noise. RT was determined from the decay curve using the interrupted noise method [15]. In addition, the objective acoustic parameters C50, C80 and STI were estimated using statistical acoustic models [16, 17].

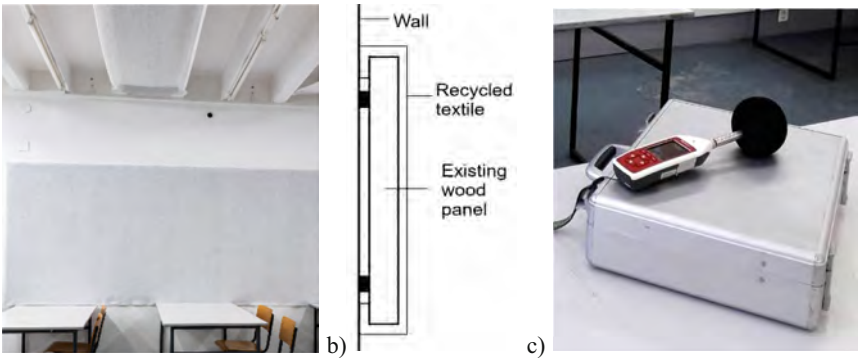


Fig. 3. In-situ classroom acoustic assessment: (a) Placing of recycled textile in the classroom; (b) Recycled textile applied around the existing plywood panel; (c) Cirrus CR:171B Class 1 sound level meter.

2.4 Thermal Conductivity Measurement

Thermal conductivity was determined experimentally under controlled laboratory conditions using a Heat Flow Meter 436/3, (Fig. 4), suitable for low- and medium-conductivity insulation materials [18]. Specimens with dimensions of 300 mm × 300 mm × 10 mm and bulk density of 40 kg/m^3 were tested. The thermal conductivity data have been reported previously [13]. In the present paper, previously obtained thermal results are incorporated together with new acoustic analyses and observations in order to provide an integrated evaluation of the recycled textile material for building applications .



Fig. 4. Sample placed in the testing instrument

3 Results and Discussion

3.1 Laboratory Sound Absorption Performance

Figure 5 shows the normal incidence sound absorption coefficients of the recycled textile (35 mm, 6 layers) compared with conventional and alternative porous materials of similar thickness. The absorption of the recycled textile is increasing with frequency, reaching ~0.8 at 2000 Hz. At low frequencies, performance is limited by the relatively small thickness, while in the mid- to high-frequency range the absorption is higher than the values reported for fibrous nonwoven [19], nonwoven PET [12] and coconut coir [22]. The material shows performance lower than that reported for glass and mineral wool [20, 21]. As these comparisons are drawn from different studies with potentially different properties and test conditions, they should be interpreted as indicative. Overall, the recycled textile shows promising mid- to high-frequency absorption, with further improvement expected at greater thickness.

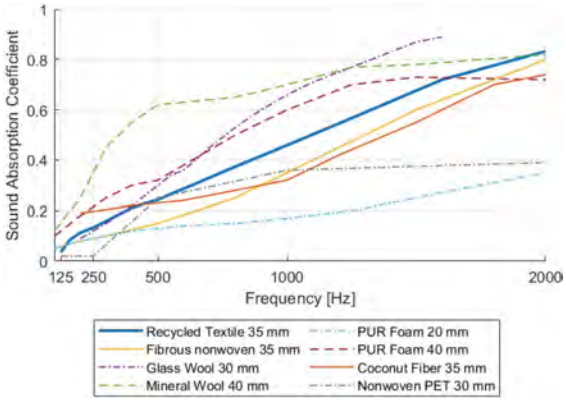


Fig. 5. Comparison of measured sound absorption coefficients for recycled textile (35 mm), fibrous nonwoven material (35 mm) [19], glass wool (30 mm) [20], mineral wool (40 mm) [21], PUR foam (20 mm and 40 mm) [21], coconut coir material (35 mm) [22] and nonwoven PET Textile (30 mm) [12].

3.2 In-Situ Acoustic Performance in the Classroom

The measured RT for several positions and estimated C50, C80 and STI for the most unfavourable seating position are shown in Fig. 6. The initially high RT decreases across all frequencies, from 3.46–1.66 s (before) to 2.05–0.86 s (after). The C50 index improves from −6.5 to −2.8 dB (before) to −3.9 to 0.9 dB (after), while C80 (included for broader acoustic characterisation) improves from −4.2 to −0.2 dB (before) to −1.4 to 4.1 dB (after), and STI improves from 0.25–0.34 to 0.31–0.42.

A value of C50 = −2 dB is considered the minimum acceptable value for speech intelligibility [23], which is achieved at mid- to high frequencies after treatment, while lower frequencies remain below this threshold. According to STI classification [17], this corresponds to a transition from bad to poor intelligibility.

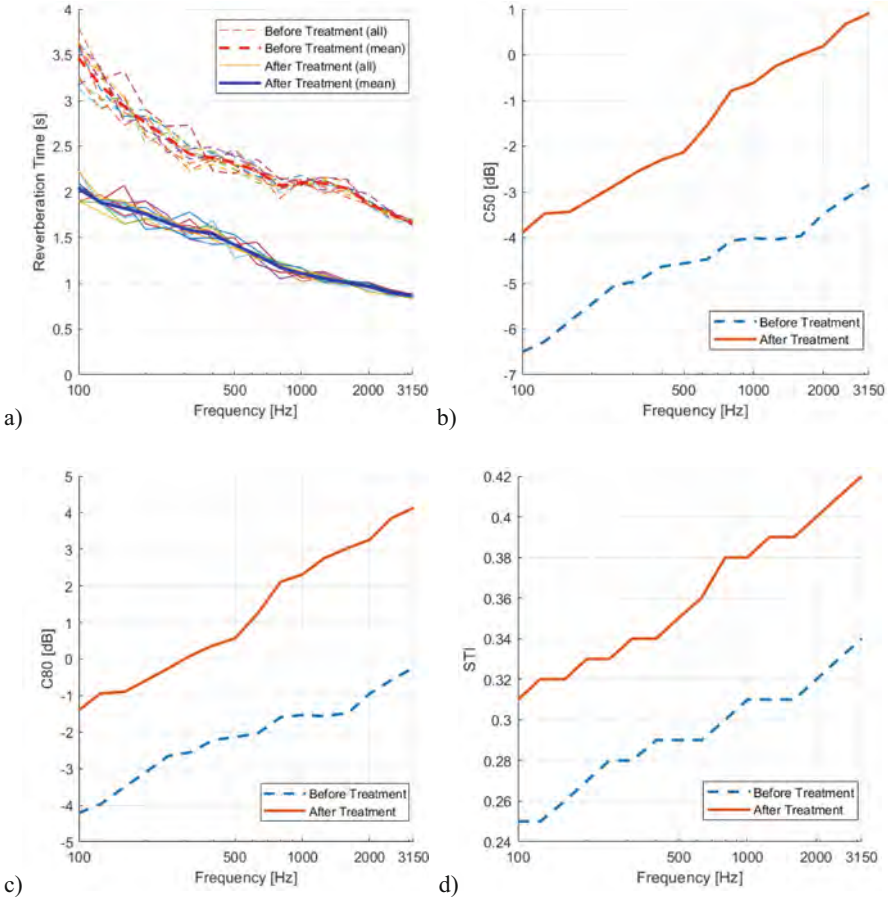


Fig. 6. Comparison of acoustic parameters before and after treatment: (a) measured reverberation time (RT) for the classroom, and (b–d) estimated parameters C50, C80 and STI for the most unfavourable seating position.

Overall, the recycled textile treatment reduced RT by approximately 35–50%, while yielding average improvements of ~3 dB in C50 and ~23% in STI. These results indicate a substantial improvement in classroom acoustics. However, optimal conditions were not achieved, especially at low frequencies, suggesting that increasing material thickness, extending surface coverage (e.g., between the ceiling ribs), or introducing an air gap behind the material would further improve acoustics.

3.3 Thermal Insulation Performance

The thermal performance of the recycled textile material was evaluated through measurement of its thermal conductivity coefficient. The obtained value of $\lambda = 0.039$ W/m·K indicates excellent thermal insulation properties, comparable to conventional insulation materials used in building applications, such as rock and glass wool (typically ~0.04 W/m·K [13]). These results demonstrate that recycled textile waste provides not only acoustic benefits but also effective thermal insulation, supporting its potential use as a dual-function material in sustainable buildings.

4 Conclusions

This study shows that recycled textile waste has promising potential for both acoustic and thermal applications in buildings. The material exhibited good mid- to high-frequency sound absorption according to the impedance tube measurements. In the classroom case study, the application of recycled textile material reduced reverberation time and improved speech-related acoustic parameters, although optimal acoustic conditions were not fully achieved. In addition, laboratory testing showed a thermal conductivity value comparable to that of conventional insulation materials.

Overall, recycled textile waste shows potential as a building material aligned with circular economy principles by supporting resource efficiency and waste valorisation. However, its economic viability and full environmental benefits should be confirmed through cost and life-cycle assessment studies. Future research should also investigate the influence of increased material thickness and optimised installation configurations to further enhance acoustic performance.

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Circular Bio-Economy: Agro-Concrete with Straw

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Abstract. The circular economy applied to building design has stimulated much research into development of lighter composite materials. Part of the aggregate or cement is replaced with biomaterials (straw, hemp, rice husk, bamboo.), industrial waste (slag, ash), as well as natural materials (perlite, vermiculite). Straw is a widely available by-product of agricultural activity. Its proper use and inclusion in innovative construction composites will reduce its inappropriate disposal and harmful impact on the environment. Several concrete mixtures were developed in which part of the aggregate was replaced with 5%, 10%, 20% and 50% straw. Wheat straw and rice straw were used. The workability and density of the fresh agro-concrete, as well as the compressive strength and thermal conductivity of hardened concrete were tested. The results for the density and strength of the samples were within the required limits for use in non-structural members. The strengths are comparable to those of traditional masonry materials, such as ceramics and aerated concrete. The recipe with 10% rice straw was the most optimal in terms of compressive strength, fresh mass workability and density. Thermal conductivity decreased with increasing percentage of straw in the cement composite. The mixture with a share of 20% rice straw had an average value of $\lambda = 0.223$ W/m·K. Finally, this type of agro-concrete possesses competence and potential for application in construction practice in new sustainable energy efficient buildings.

Keywords: Straw · Agro-concrete · Compressive Strength · Thermal Conductivity · Biomaterials

1 Introduction

The efficiency of the use of materials and limited resources is significant in today's world, where conventional resources are limited and there is a need to minimize the effects of human activities on the environment. Efficient reuse of materials has the potential to be an essential part of our lives and the engineering profession has a key role in shaping a world that is attuned to nature. Due to population growth and food production, waste is

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also growing, and the methods of disposing of it are often harmful to the environment. On the other hand, the unsustainability of a large number of processes in the world construction have the same causes and consequences. These two problems can find a common solution, for a better, more sustainable and cleaner future, including aspects of circular economy [1].

The use of agricultural by-products in construction has enormous potential for reducing the global pollution problem. There are numerous agro-wastes such as seeds, husks, straws and other materials, which can find serious application in construction. The oldest forms of fibers used in building materials (such as bricks, blocks, and mortar) are straw and animal fibers. Plant and cellulosic fibers have significant advantages, most importantly they are readily available, bio-renewable and relatively inexpensive. They have interesting and applicable physical and mechanical properties, such as low density, while maintaining satisfactory strength. Plant fibers can be found in various shapes and morphologies, diameters, lengths and groupings. Examples of this are straws, bundles, pulp and the like. Their surface can be easily modified to exhibit hydrophilic or hydrophobic properties [2]

Traditionally, rigid materials in construction have been reinforced for centuries using plant fibers throughout recorded history. However, the concept of plant fibers in cement composites was developed in the 1940s, when this type of material was considered a potential replacement for asbestos-cement fiber as a filler [3]. Since then, considerable effort has been invested in finding some application of plant fibers as a type of filler in construction materials. The use of natural fibers, such as hemp, bamboo, wheat straw, jute, coconut pulp and shells, palm kernels, nuts such as pistachios, in composites is a research topic that has been of interest to numerous scientists. The studies of Chennakesava Rao & Prabath [4], Rahim et al. [5], Petkova-Slipets et al. [6], Shea et al. [7] are some of them, where partial or complete replacement of stone aggregates was researched. Natural fibers, including straw, are organic materials whose main components are cellulose, hemicellulose, and lignin. Natural fibers can be processed or unprocessed. They provide a renewable and widely available source of fibers for mortars and concretes at low prices. The advantages of straw are that it is a renewable, green material and represents an excellent alternative approach to various problems in construction. It possesses good thermal insulation and acoustic characteristics and is a solid choice for use in panels. The most widely used and simplest way to deal with the problem of grain waste is its burning. Over 150 million tons of straw are produced in North America annually, and most of it is burned, which is a highly unsustainable way to deal with such a problem [8]. Around 20% of the total biomass produced in the European Union countries is straw [9].

The focus of this research is centered around the use of the straw, but in a new connotation, as a composite for partition blocks based on cementitious non-structural agro-concrete.

2 Materials and Methods

2.1 Materials for Agro-Concrete

Straw as a material generally contains large amounts of cellulose, hemicellulose and lignin. Among them, cellulose and hemicellulose are hydrolyzed in water and release monosaccharides, such as glucose, xylose, arabinose and galactose, which are collectively known as cellulose sugar, which adversely affects the hydration, binding and hardening process of cement [10].

Two types of straw were selected for aggregate replacement for the tests: wheat straw (WS) in coarse form and machine-processed and crushed rice straw (RS).

Wheat straw (WS) is an agricultural by-product that possesses numerous qualities that can be used in the construction of structures. WS is a traditional material, which has been used by many cultures throughout the development of civilization and is applied for many different purposes [2, 8, 9]. In rural areas, it was used as a roofing material. WS is also used as a filling for panels - partitions, which are a type of green material. After the end of the exploitation, such panels can be recycled and reused.

The coarse WS in this research was treated with sodium metaphosphate – water glass, in order to reduce its water permeability, i.e. to crystallize, which brings its properties closer to those of the standard aggregate used in concrete. Since the WS comes in relatively large pieces, before use it was processed, cut with scissors and crushed to pieces with a dimension of up to 5 cm, Fig. 1b.

Rice straw (RS) is a by-product of rice production and processing during harvesting. Based on various studies, the density of RS can vary from 13 to 18 kg/m^3, depending on the different forms it can have. Chopped and shredded RS can have a significantly higher density. The rice straw has a density that varies between 86 and 114 kg/m^3. Unprocessed samples have a lower density. Chemically, it consists of cellulose, hemicellulose, lignin, lipids, proteins, simple sugars, water and other carbon compounds [11]. The concentration of the components depends on the growth stage, plant type and growing conditions. It is characterized by a good calorific value when burned and therefore finds application as a bioenergy fuel. The most common way to dispose of waste from rice processing is its burning, which is an emission of harmful gases.

The fine rice straw used in this paper is taken as waste material from a processing plant. The chopped rice straw was stored in a dry condition, in a room with low humidity. It was not amenable to treatment with sodium metaphosphate, since it is an open material, it is not porous to that extent in its natural form, and due to its granulation and natural texture, is used in the tests as a direct replacement for a percentage of the aggregate in the first - finest fraction, Fig. 1c.

2.2 Mix Designs

The recipes include replacement of the stone aggregate with 5% WS, and RS with 5%, 10%, 20% and 50% of the total amount of aggregate. All materials used in the experimental research are in accordance with the applicable standard for concrete production and definition of concrete as a construction product [12].

Cement type CEM I 52.5 R is used as a binder. It is a pure Portland cement with a small addition of gypsum, to regulate the setting time, and up to 5% other mineral additives. It is characterized by high strength characteristics (in the early and late stages), but also by a relatively high heat of hydration. The material complies with MKS EN-197-1 [13]. The aggregate used is crushed stone from the Govrlevo limestone quarry, produced by the cement plant "Usje" AD Skopje. It is a limestone crushed stone aggregate with a maximum grain diameter of 16 mm, characterized by good physical and strength characteristics. It is certified according to MKS EN 12620 + A1:2009 [14] for use in the production of concrete and as an aggregate for unbound and hydraulically bound materials. In order to improve the workability and embeddability of the composite, the additive Superfluid 21M1M ECO was used, in an amount of 0.5% of the weight of the cement, respectively for each mixture. The amount of water was defined during the mixing itself in order to obtain a homogeneous mixture.



Fig. 1. a) Stone aggregate – fraction 2, b) wheat straw, c) rice straw.

2.3 Methods

The fresh concrete mass, its density and workability were tested, as well as the bulk density and compressive strength were measured in laboratory conditions. For determining consistency of the fresh agro-concrete, "slump test" was performed according to MKS EN 12350-2 in a metal mold on a flat surface. Then, the samples for testing compressive strength were prepared in accordance with MKS EN 12390-1 [15]. The samples had dimensions of 15/15/15 cm and each sample is marked, as prescribed by the MKS EN 12350-1 standard [16]. The compressive strength of the test specimens was determined

in accordance with the MKS EN 12390-3 [17], Fig. 2b. The strength can be tested at 3, 7 and 28 days, but for the purposes of this paper, the final strength was checked at 28 days.



Fig. 2. Samples for testing: a) Thermal conductivity, b) Compressive strength, c) Samples with 50% of rice straw.

In order to investigate the impact of the different percentage of straw on the thermal properties of this type of composite, 3 samples of each mixture were prepared, in which 5%, 10%, 20% and 50% respectively of the aggregate volume (fraction 0–4 mm) was replaced with rice straw. The thermal properties were tested on samples with basic dimensions of 300 mm × 300 mm, Fig. 2a. They were cured in laboratory for 28 days under standard conditions, until the composite mass was completely hardened. The experimental test was performed according to a standardized procedure, with the Heat Flow Meter instrument, in the Laboratory for Insulating Materials, Civil Engineering Physics and Chemistry at the Faculty of Civil Engineering, UKIM in Skopje, as described in [18].

3 Results and Discussion

3.1 Agro-Concrete with Wheat Straw (WS)

The average mass, density and compressive strength of five samples made of agro-concrete with 5% WS are presented in Table 1.

Table 1. Average properties of samples with WS.

Sample	Mass (g)	Density (kg/m^3)	Slump test (cm)	Compressive strength (MPa)
Standard	8069	2391	19	42.6
5% WS	7382	2187	19	8.4

The bulk density of the fresh concrete mix decreased with increasing percentage of WS in the composite content, and the same trend is observed in samples of hardened concrete after 28 days.

The samples with WS do not show satisfactory consistency of results and retain a more serious amount of moisture, and physically have difficulty maintaining the shape of the mold – they are susceptible to crumbling. This made it unsuitable for continuing the tests with higher percentages of WS after the same test, since the change in strength with 5% replacement with WS is extremely dramatic. Namely, the average strength of 8.4 MPa for the samples with 5% WS is 5.1 times lower than the average strength of the reference samples (42.6 MPa), Table 1.

3.2 Agro-Concrete with Rice Straw (RS)

The average mass, density, slump test and compressive strength of the samples made of agro-concrete with rice straw(RS) of 5%, 10%, 20% and 50% are presented in Table 2. For each of the recipes, five to nine samples were tested.

Increasing the percentage of RS resulted in a reduced consistency, i.e. workability of the cement mixture. The slump test of the cement composite with RS after 10 s was 9 cm for the sample with 50%, 18 cm for the sample with 20% RS and 19 cm for the sample with 10% and 5% rice straw. Rice straw absorbed moisture from the concrete when added and reduced the amount of free water.

Table 2. Average properties of samples with rice straw (RS).

Sample	Mass (g)	Density (kg/m^3)	Slump test (cm)	Compressive strength (MPa)
Standard	8069	2390.8	19	42.6
5% RS	6402	1896.9	19	12.7
10% RS	5321.7	1576.8	19	3.4
20% RS	4686.9	1388.7	18	/
50% RS	4110.2	1217.8	9	/

The workability shown through slump tests indicated that the mixtures with 5% and 10% replacement of the first fraction with RS were within the normal parameters. The attempt with 50% gave a worse result than the others.

Samples with 5% RS had a lower mass by an average of 290 kg/m^3 per sample than samples with 5% WS of the same volume.

The bulk density of the test specimens was also examined. It was noted that the samples with WS did not show a significant drop in bulk density, but the specimens with RS gave a constant and regular drop in bulk density. All samples belong to the so-called lightweight concretes, having densities ranging 300 to 2000 kg/m^3 [19].

Regarding the mechanical properties, tests showed that with the increase of RS in the concrete mixture, the strength decreased. The test specimens with 5% showed an average compressive strength of 12.7 MPa, while those with 10% replacement of the first fraction had an average compressive strength of 3.4 MPa. They showed properties similar to those of traditional materials for masonry units in construction, such as: ceramic blocks, autoclaved concrete blocks and other materials for non-structural use. The samples with

50% RS after hardening of the material clearly showed lack of consistency. Friability and separation of the stone aggregate could be observed on the surface, indicating the unsuitability of the material for further use (Fig. 2c). The results for thermal conductivity were performed on samples with 10%, 20% and 50% of RS. The average results with standard deviations are presented in Fig. 3.

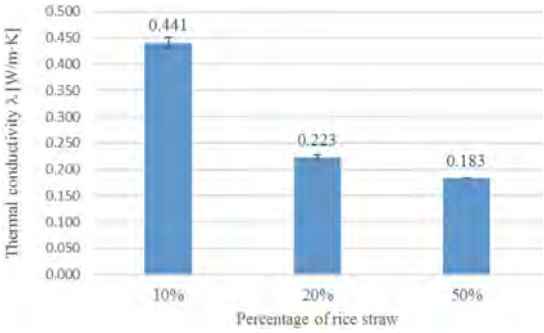


Fig. 3. Average thermal conductivity of samples with different percentage of RS.

They show that the agro-concrete had better thermal insulation properties than the traditional concrete for construction, usually referred as 2 W/m·K [19]. The thermal conductivity decreased with increasing percentage of RS in the cement composites. The most suitable recipe was the one with a share of 20% RS, presenting average value of the thermal conductivity $\lambda = 0.223$ W/m·K, since the samples with 50% didn't show stability in shape and strength

4 Conclusions

This study examines the possibility of applying the concept of circular economy in the production of various types of new cement composites. The research contributes to the creation of opportunities for the application of straw, a waste from agriculture that is practically unusable, as a substitute for aggregate in agro-concrete. An experimental laboratory study was conducted on concrete containing a partial replacement of the aggregate with different percentages of straw: 5%, 10%, 20% and 50%. The properties of the concrete mixtures, as well as of the hardened concrete, were analysed. The favourable thermal insulation characteristics are largely due to the porous structure of the straw. However, as the percentage of straw increases, the strength decreases, so it is recommended to limit the use of this material to elements that will not be subjected to high structural loads. Comparatively, this strength is satisfactory for use only for non-load-bearing elements, masonry units, considering that lightweight blocks and ceramics have compressive strengths varying from 3 to 7 MPa. The application of this composite would be most acceptable in masonry blocks in partition and facade walls, in order to make the most of its potential for good thermal insulation. The demonstration of the physical and mechanical properties of concrete containing a variable amount of waste

straw as an aggregate allows the use of this material for production of an ecological material with sustainable significance. This approach also offers an opportunity to decrease the problem of excessive straw waste, which is usually burned in landfills and causes creation of greenhouse gases. Therefore, the use of these materials will contribute to ecological and safer living environment, emphasizing the role of circular economy in construction. These ecological materials can further be used for non-structural elements in high-rise buildings, but also for paving larger areas, curbs, sidewalks, etc.

This study faces some limitations as well: thermal conductivity was not measured on the control samples without straw and on the samples with wheat straw due to the limitations of the instrument, only 5% wheat straw was analysed with 5% as a replacement for the first fraction in the concrete mixture etc.

The general conclusion is that the analysed agro-concrete justifies the use of straw in construction. This type of composite has competence and potential for application in everyday construction practice. Given that the straw is a widely available by-product at a low price, it can show high competitiveness in the insulation materials market. At the same time, cement composites that incorporate straw as a renewable resource into their matrix, will help eradicate the negative impact that the construction industry has had so far.

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Manufacturing Techniques for High-Performance Earthen Materials

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Abstract. Efficient manufacturing techniques for earthen materials are essential for their contemporary application in load-bearing construction. However, due to the limited technological development that has characterised earthen construction over the past centuries, existing manufacturing methods remain poorly adapted to modern building requirements. This paper therefore examines contemporary manufacturing techniques for high-performance earthen materials. Although earth offers considerable ecological advantages, such as low embodied energy, full recyclability and regional availability, traditional techniques like rammed earth or cob are often incompatible with present-day demands for mechanical performance, speed, costs and scalability. As a result, the inherently sustainable material earth, largely displaced during nineteenth-century industrialisation, continues to be underutilised despite its relevance in addressing current challenges related to climate change and resource scarcity. The study investigates three emerging manufacturing approaches: highly compacted earth, poured earth, and earthen additive manufacturing, focusing on their potential to transform earth into a material suitable for industrialised, efficient, and automated construction processes. Employing a methodology that combines material testing, process evaluation, and comparative performance assessment, the research identifies significant improvements in mechanical strength, stiffness, and manufacturing efficiency enabled by the studied technologies. The findings suggest that innovative manufacturing processes not only enhance the structural and functional capabilities of earthen materials but also open up new areas of applications previously unattainable with conventional methods. The paper concludes that modernised fabrication strategies have the potential to re-establish earth as a viable, future-oriented building material and to contribute meaningfully to sustainable construction.

Keywords: earthen construction · material innovation · poured earth · compacted earth · additive manufacturing

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1 Introduction

Earth is among the oldest building materials in human history, with the earliest evidence of its use dating back to approximately 10,000 BCE in Southwest Asia [1]. The limited industrialisation of earthen construction led to its widespread displacement in industrialised countries by modern materials such as brick, concrete, and calcium silicate masonry, offering high mechanical performance, efficient manufacturing, and economic advantages and therefore continue to dominate the construction sector today [2].

At the same time, the ecological drawbacks of conventional building materials are increasingly coming into focus considering anthropogenic climate change, resource scarcity, and ambitious sustainability targets. Earthen materials offer considerable advantages in this context, including low embodied energy, full recyclability, and regional availability. Nevertheless, their application in contemporary construction remains largely limited to niche use cases.

In Germany, approximately 97% of approved new buildings are low-rise structures of up to three storeys [3]. For these applications, conventional materials are often over dimensioned, while earthen materials would suffice. However, these materials are rarely employed, as traditional earthen construction techniques fail to satisfy present-day requirements in terms of construction speed, cost efficiency, scalability, and compatibility with industrialised building processes. Consequently, the limitations of earth as a building material lie less in its material properties than in the insufficient development of its manufacturing and processing techniques.

Regarding this background, the present study investigates contemporary high-performance manufacturing techniques with the potential to industrialise earthen construction and make it competitive with established building systems. It is assumed that existing infrastructures and processes from concrete and masonry construction, as well as additive manufacturing (AM), can act as catalysts for modern earthen construction. The study focuses on three emerging approaches: highly compacted earth blocks (HCEBs), poured earth (PE), and earthen AM. These approaches are systematically analysed and discussed regarding their manufacturing processes, performance characteristics, and their positioning relative to conventional construction methods.

2 High-Performance Manufacturing Techniques

Traditional earthen construction techniques are diverse and time-tested, yet they require extensive labour and specialised knowledge. In contemporary practice, earth is primarily used in non-load-bearing applications such as plasters and infill systems, while structural applications remain limited.

Recent developments aim to overcome these constraints through industrialised and performance-oriented approaches. HCEBs, PE systems, and earthen AM represent emerging strategies that seek to enhance mechanical performance, process efficiency, and reproducibility. By integrating standardised manufacturing methods and controlled material compositions, these approaches move earthen construction towards higher structural reliability and broader applicability within modern building practice.

2.1 Poured Earth (PE)

Definition. PE – also referred to as liquid earth, cast earth or earth concrete – is a liquefied earthen material that can be cast into formwork. Liquefaction is achieved either by increasing the water content or by incorporating additives such as dispersants and setting accelerators. Figure 1a illustrates the typical processing consistency of PE and Fig. 1b the geometric precision achievable. While increased water content leads to prolonged drying times and a higher risk of shrinkage cracking, using additives can significantly modify the positive material properties, depending on their type and dosage.

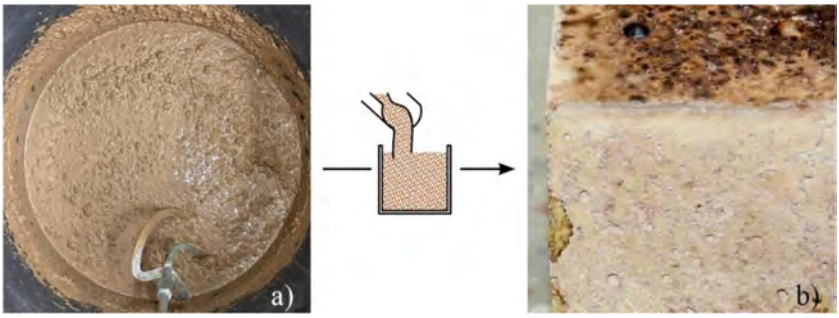


Fig. 1. a) processing consistency of PE and b) detailed view of the specimen edge [Photo a): Rieke Platthaus; Photo b): Charlotte Bitterer].

State of the Art. Liquefying earth enables a rapidly applicable and environmentally friendly alternative to conventional building materials such as concrete. In the 1990s, »Cast Earth« was developed as one of the first documented systems combining soil with calcined gypsum and a retarder [4]. While demonstrating the feasibility of castable earthen materials, such approaches relied on chemical binders that substantially altered the intrinsic properties of earth. Studies have shown that chemical binders negatively affect recyclability and increase the carbon footprint of earthen building materials [5]. In addition, stabilising additives such as cement, gypsum, or polymer dispersions have been reported to reduce the water vapor adsorption capacity of earthen plasters [6], thereby compromising key ecological and hygrothermal advantages.

As a result, research on additive-induced liquefaction without chemical binders has gained increasing attention. Recent approaches therefore investigate environmentally compatible dispersing agents such as alginates, oak tannins, and sugarcane molasses [7, 8]. The compressive strengths achieved with these additives are comparable to those of rammed earth, typically in the range of 1.5–3 MPa.

Beyond material performance, PE enables the use of existing infrastructure from the concrete industry (e.g. truck mixers, formwork, and compaction systems) thereby offering significant potential for industrialised earthen construction. Pilot projects have already demonstrated the successful adaptation of these technologies [9].

Key Elements. Compared to rammed earth, which typically achieves manufacturing rates of approximately 4 m^3/h, PE compacted by vibration can be manufactured at rates

approximately ten times higher, according to manufacturer specifications [10]. Pumpable mixtures enable additional efficiency gains in handling and placement.

At present, PE is largely limited to low-rise construction due to current compressive strength levels. However, as low-rise buildings dominate new construction in Germany, PE holds considerable implementation potential.

Despite these advantages, several research gaps remain. The interactions between additives and earthen constituents are not yet fully understood, and standardised testing procedures are currently lacking, although initial proposals have been made [11]. However, long-term durability, cost structures, drying behaviour and reinforcement strategies require further investigation. In particular, drying represents a major challenge for on-site applications, strongly influencing construction speed and dimensional stability.

2.2 Additive Manufactured (AM) Earth

Definition. AM advances earthen construction methods and opens new architectural possibilities. It produces digitally designed 3D-models through layer-by-layer deposition, enabling precise geometry and controlled material placement (Fig. 2).

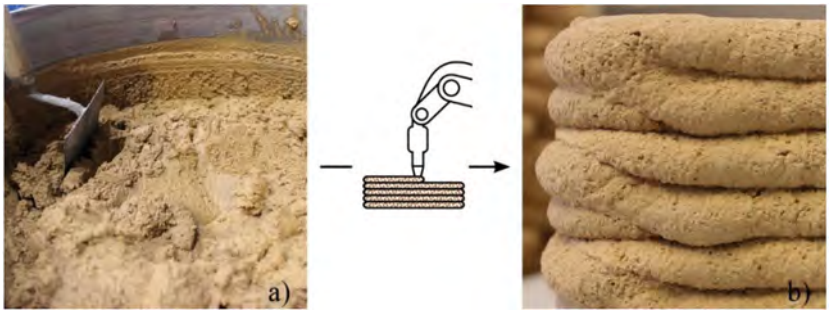


Fig. 2. a) processing consistency of earth for AM and b) detailed view of the specimen edge [Photos: Leonie Gleiser].

State of the Art. The primary motivation for implementing AM in construction is addressing skilled labour shortages while increasing efficiency and design flexibility. Traditional earthen techniques require extensive craftsmanship and specialised knowledge. AM enables realisation of complex, individualised designs while reducing material consumption and construction time [12]. Extrusion-based AM, widely established in construction, supports applications such as prefabrication, formwork, and on-site fabrication. While concrete is currently the most widely applied material in large-scale construction, earth offers sustainable alternatives for AM processes [13, 14]. Earthen materials provide further environmental benefits through local availability, reducing transport-related emissions and waste, supporting circular construction [14].

Material composition and consistency in extrusion-based AM must satisfy a defined rheological window ensuring three key properties: extrudability (dimensionally stable

filament without cracking), pumpability (material transport without property alteration), and buildability (layer capacity to sustain subsequent layers without deformation) [13]. The use of earth introduces challenges regarding material composition, building components, and process adjustments. The paradox of extrudability and buildability, requiring both flowability for extrusion and rapid stiffening for stability, raises questions concerning structural build-up through time-dependent yield stress increase.

The fluid mixes required for extrusion increase shrinkage and reduce early dimensional stability. Dispersion and coagulation strategies using earth and sustainable additives from PE are being explored to limit shrinkage and speed up setting in AM. Additionally, 3D-printed elements exhibit high anisotropy from layer-by-layer deposition, resulting in direction-dependent strength properties [15]. Manufacturing and installation orientations must therefore be considered to optimise structural performance. Compared with conventional massive earth, additive manufactured earth shows promising thermal performance and a comparable density–thermal conductivity relationship, although further research is still required.

Key Elements. AM offers significant potential in construction through automation, digital precision, and material efficiency. In the context of rising housing demand and the need for sustainable, cost-efficient methods, AM with earthen materials represents a promising solution, enabling resource-efficient manufacturing with high design flexibility for project-specific architectural requirements. 82% of historical earthen manufacturing techniques like adobe and cob are suitable for AM due to their consistency and workability [12]. However, most large-scale AM still relies on cement-based materials and thus mirrors the footprint of conventional concrete construction. Earthen AM instead removes formwork and energy-intensive binders, enabling locally sourced, circular, low-carbon building. It can replace conventional mineral-based solid construction, including complex formwork and manual adobe or mortar work, by enabling monolithic, formwork-free construction with minimal embodied energy.

Key research gaps concern the limited understanding of process–material interactions and structural performance of additively manufactured earth elements. Open questions remain regarding standardised testing methods, long-term durability, reinforcement strategies, and scalability. Material consistency, delivery systems, and geometric constraints present significant challenges [12]. The extrusion process requires a defined rheological window that restricts buildability and increases susceptibility to shrinkage and cracking during drying [14]. Additionally, low printing speeds and long drying times also limit efficient on-site workflows. Overall, earthen AM marks a shift toward materially appropriate digital construction, combining local circular resources with computational design and automated fabrication.

2.3 Highly Compressed Earth Blocks (HCEBs)

Definition and State of the Art. HCEBs represent an advanced development of compressed earth blocks (CEBs), manufactured in rigid steel-molds using manual or hydraulic presses, aiming to significantly enhance mechanical performance through increased densification rather than chemical stabilisation [16, 17]. Due to their relatively high degree of industrialisation and compatibility with established construction

workflows, they are considered one of the earthen construction methods with the greatest potential for acceptance in contemporary architecture [18]. While CEBs are typically compacted at pressures between 2 and 6 MPa [19, 20], increasing compaction stress from 5 to 20 MPa has been shown to yield compressive strength increases of up to 70% [21].

In addition to significantly higher compaction pressures, HCEBs are characterised by lower manufacturing water content and distinct material behaviour during pressing compared to conventional CEBs. The raw material typically consists of a well-graded earth mixture with a clay content below 25% [20] and a moisture content below the Proctor optimum, reflecting the high compaction energies applied. Achieving high mechanical performance further requires a high degree of homogenisation, typically through pulverisation or high-rpm mixing. This preparation results in a crumbly to powdery consistency of the fresh material (Fig. 3a). The resulting blocks exhibit a dense, stone-like appearance with sharply defined edges and smooth surfaces (Fig. 3b).

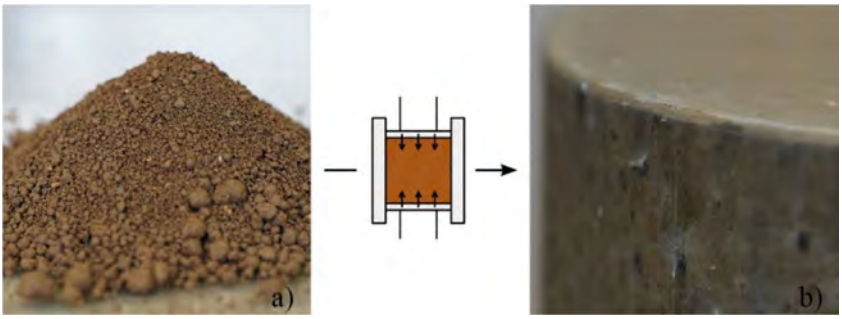


Fig. 3. a) Homogenised material right before production, b) compressed earth block with sharp edges and $f_c > 10$ MPa [Photos: Konstantin Nille-Hauf].

Key Elements. The pressing process employs compaction pressures that significantly exceed conventional values – often by an order of magnitude - using rigid steel molds and high-capacity hydraulic presses. Although presses capable of reaching compaction stresses up to 25 MPa are commercially available, they are generally designed for calcium silicate masonry. These pressure levels impose substantially increased demands on press force capacity and mould strength. As the internal stress state during pressing depends on the properties of the earth mixture as well as on mould geometry and surface conditions, a hydrostatic pressure state is recommended to assumed on the safe side for mould design. Whereas conventional CEBs are typically compacted only to the point at which air-filled macropores are eliminated or just little beyond, HCEBs are compressed way beyond this stage until pore water pressure develops and a consolidation process is initiated. With progressing consolidation, material density continues to increase, enabling further improvements in compressive strength [16, 22], but also yielding to longer pressing processes and dropping manufacturing rates. High compaction results in a reduction of microporosity, leading to increased particle contact, interlocking, and frictional resistance.

Classification. Within the broader spectrum of masonry materials, HCEBs occupy an intermediate position between conventional earthen products and industrial masonry units. In terms of compressive strength and stiffness, they may reach values of up to 20 MPa/4000 MPa (f/E) [17, 22]. These performance levels are comparable to those of calcium silicate and fired clay bricks, while clearly exceeding the properties of unstabilised CEBs. Compared to aerated concrete (SFK2–8, DIN 4165–100), HCEBs exhibit substantially higher density as well as superior mechanical performance.

3 Conclusion

This review examined three contemporary high-performance earthen construction approaches: HCEBs, PE, and earthen AM. Each method represents a different level of technological maturity and industrial readiness.

PE enables compatibility with existing concrete infrastructure and improves manufacturing efficiency yet remains limited by compressive strength, drying behaviour, additive interactions, and the lack of standardised testing procedures. Earthen AM presents the most transformative potential through digital, reproducible, formwork-free fabrication with reduced labour force, yet it faces significant challenges regarding rheology, mechanical properties, printing speed, and regulatory integration. However, HCEBs currently offer the most reliable and reproducible strength improvements, achieving structural capacities suitable for load-bearing applications through increased densification rather than chemical stabilisation.

Overall, the primary limitation of earthen construction lies not in the material itself but in the optimisation and industrialisation of its manufacturing processes. Advancing standardisation, improving material-process understanding, and developing scalable production strategies will be essential to establish earth as a competitive and climate-responsive building material in contemporary construction.

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Development of Eco-Friendly Gypsum Composite Using Gypsum Binder and Gypsum Waste Aggregates

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Abstract. The development of sustainable building materials is increasingly focused on integrating regenerative resources and secondary raw materials obtained through industrial symbiosis. In this context, gypsum composites represent a promising solution for reducing environmental impact in the construction sec-tor. The raw materials used for gypsum composites include not only building gypsum (BG) but also gypsum-based demolition waste (GDW). In this study, gypsum composites were produced using BG binder combined with varying proportions of fine recycled fillers derived from GDW. The primary aim was to evaluate whether incorporating GDW can reduce environ-mental impact while maintaining mechanical performance comparable to reference gypsum composites without recycled material. BG was substituted with 10, 20, 30, and 40 wt% GDW, and the gypsum-to-water (G/W) ratio varied from 0.5 to 0.7. For each composition, nine samples were tested. The structural and mechanical behavior of the composites was assessed using X-ray diffraction (XRD), scanning electron microscopy (SEM), compressive strength tests, hydration temperature measurements, and loss-on-ignition analysis. The results showed that the proportion of recycled fillers significantly influenced the key material properties. Notably, a slight improvement in compressive strength was observed in the eco-friendly composites: the reference sample achieved 13.85 MPa, whereas the composite containing 10 wt% GDW reached 15.95 MPa. However, higher GDW content led to a reduction in com-pressive strength. This increase can be attributed to the micro-filler and nucleation effects of GDW, which produced denser microstructure and improved bonding characteristics.

Keywords: Gypsum composite · Secondary raw materials · Building gypsum binder · Gypsum boarding waste aggregates

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1 Introduction

Gypsum, a long-used construction material, can significantly improve its sustainability through circular-economy strategies, including recycling and the partial replacement of raw gypsum with various construction and demolition wastes. A study [1] shows that gypsum composites and prefabricated elements can incorporate a wide range of waste materials—such as concrete, ceramics, glass, plastics, and insulation materials. -while maintaining viable mechanical performance for building applications. Villiorya et al. [2] showed that adding ceramic, concrete, and expanded polystyrene (EPS) construction waste to gypsum can improve density, mechanical strength, and thermal behavior. Using the best mixture, they produced a sandwich-type gypsum block, demonstrating both performance gains and environmental benefits through waste reuse. A related study [3] tested lightweight fillers such as silica sand, perlite, expanded clay, and waste polyurethane foam. Filler porosity was found to shape the gypsum microstructure, producing smaller, denser crystals around porous particles. Mortar with polyurethane foam had the lowest strength (2.9 MPa at 7 days) but the best thermal conductivity (0.211 W/m·K). Pedreño-Rojas et al. [4] showed that recycled gypsum combined with wood waste can produce eco-efficient gypsum composites with lower density, improved thermal insulation, and adequate mechanical performance for building applications. The study [5] evaluates the incorporation of ceramic and EPS waste into gypsum products, showing that up to 50% ceramic waste maintains core properties while improving hardness and reducing water absorption, and EPS additions lower density and enhance thermal performance, supporting future inclusion in a national recycling database.

Several studies have demonstrated that gypsum derived from construction and demolition waste (GDW) can be effectively reused as a gypsum binder, showing technical feasibility, stable performance across multiple recycling cycles, and compatibility with various additives for producing sustainable construction materials. Bumanis et al. [6] stated that GDW can be recycled into a functional gypsum binder, though its performance depends strongly on gypsum purity, fineness, and the required water-to-gypsum ratio. Laboratory results show that recycled GDW, after separation, crushing, milling, and controlled heat treatment, can achieve strengths up to 3.7 MPa, demonstrating its potential as a secondary raw material within a circular gypsum life cycle. Study made by Erbs et al. [7] shows that gypsum waste can be successfully recycled up to three cycles without significant loss of physical or mechanical performance, confirming the technical viability of repeated reuse. These findings highlight the potential for producing new building components with high recycled-gypsum content, supporting circular-economy strategies and creating new commercial opportunities in the construction sector. Crushed plasterboard waste is a viable sulphate source for activating pozzolanic binders made from slag and cement bypass dust. Hughes et al. [8] showed that a mix containing 15% gypsum, 5% bypass dust, and 80% basic oxygen slag performs on par with conventional cement in road construction, offering a cost-efficient and sustainable reuse route for plasterboard gypsum and other industrial by-products. In a similar study, Zaharieva et al. [9] found that recycled gypsum from plasterboard waste can be effectively used in blended green binders, providing fast-setting behavior and achieving strengths up to 30 MPa when combined with natural zeolite.

The aim of this study is to examine how incorporating gypsum-based demolition waste (GDW) as a recycled filler influences the key physical, mechanical, and microstructural properties of gypsum-based building composites, and to determine whether these changes support the development of more sustainable construction materials.

2 Materials and Methods

2.1 Characterization of Initial Materials

The X-ray diffraction pattern of the commercial building gypsum shows reflections characteristic of calcium sulfate hemihydrate (bassanite, $CaSO_4 \cdot 0.5H_2O$), confirming that the material is predominantly in the semihydrate form (Fig. 1a). The main diffraction peaks appear at approximately $2\theta \approx 14.7°$, 25.5°, 29.7°, and 31.2°, corresponding to the most intense bassanite planes. Some residual peaks of dolomite ($CaMg(CO_3)_2$), are detected as well. In the building gypsum system, the semihydrate phase remained predominant despite the incorporation of dolomite.

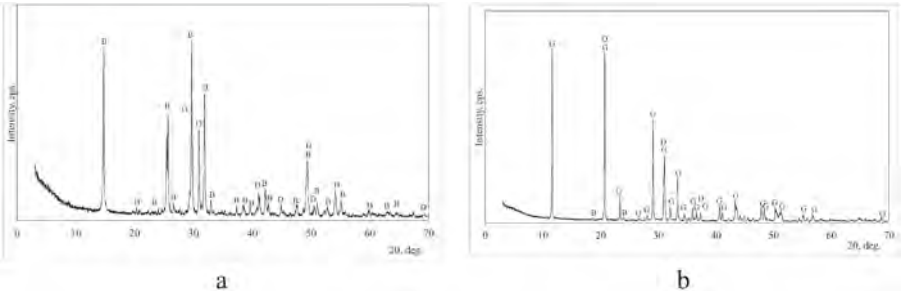


Fig. 1. X-ray diffraction patterns of building gypsum (a) gypsum-based demolition waste (b): G - gypsum $CaSO_4 \cdot 2H_2O$ (33–331), B - basanite $CaSO_4 \cdot 0.5H_2O$ (33–310), D - dolomite $CaMg(CO_3)_2$ (74–1687), Q - quartz SiO_2 (72–916).

For the gypsum-based demolition waste (Fig. 1b), the hydrated mineral forms were identified as being dominated by the $CaSO_4 \cdot 2H_2O$ dihydrate phase, accompanied by only minor amounts of dolomite and quartz. The loss on ignition (LOI) for GDW consisted of 16.36.

SEM images (Fig. 2a) show that BG exhibits sharp-edged, plate-like crystals forming a structure composed of particles of varying size. The crystals are typically a few micrometers in size and display an irregular morphology characteristic of β-type hemihydrate. A similar form of building-gypsum crystals, such as flaky particles composed of small intergrown crystals, was also reported by Singh et al. [10]. In contrast, the GDW (Fig. 2b) displays a markedly more homogeneous microstructure. The crystalline framework is disrupted, characterized by fragmented needle-like forms and irregular particle boundaries. The dry bulk density of the GDW is 581.01 kg/m^3.

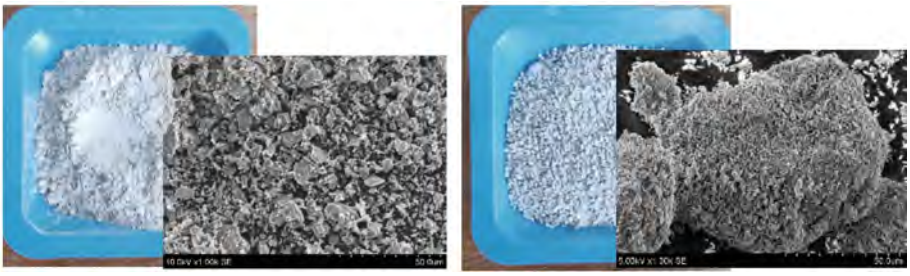


Fig. 2. Microstructure of building gypsum (a) and gypsum-based demolition waste (b).

2.2 Preparation for Forming Mixtures

Table 1 outlines the formulation of the gypsum composites prepared using varying proportions of building gypsum (BG) and gypsum-based demolition waste (GDW). The mixtures range from a reference sample composed entirely of BG (0GDW) to blends containing up to 40% GDW (40GDW).

Table 1. The composition of initial materials for gypsum composite.

Sample	BG (%)	GDW (%)	W/G
0GDW	100	0	0.5
10GDW	90	10	0.5
20GDW	80	20	0.5
30GDW	70	30	0.6
40GDW	60	40	0.7

As the GDW content increases, the **water-to-gypsum ratio (W/G)** is gradually adjusted to ensure workable consistency. Samples with lower GDW content (10–20%) maintain a constant W/G ratio of 0.5, while higher GDW substitutions require increased water demand (0.6–0.7) associated with recycled gypsum waste.

Figure 3 presents the prepared gypsum composite specimens containing increasing proportions of GDW. The size of samples was 4 × 4 × 4 cm.

2.3 Test Methods

X-ray diffraction (XRD) analysis was performed using a Bruker AXS D8 diffractometer with CuKα radiation and a 0.02 mm Ni filter. The detector step size was 0.02°, counting time 0.5 s, and the operating conditions were 40 kV and 40 mA. The amount of bound water (loss on ignition) was determined by heating the material to 400 °C. The microstructure was examined using an FEI Quanta 200F SEM equipped with a Schottky field-emission gun (FEG). Imaging was performed in high-vacuum mode at 5 kV. Compressive strength tests were conducted after 7 days of curing according to LST EN 12390-3:2019, using 4 × 4 × 4 cm cubic specimens and a Zwick Roell testing machine.



Fig. 3. The picture of gypsum composites samples.

3 Results and Discussions

Figure 4 illustrates the evolution of hydration temperature for the gypsum composite mixtures incorporating increasing proportions of GDW.

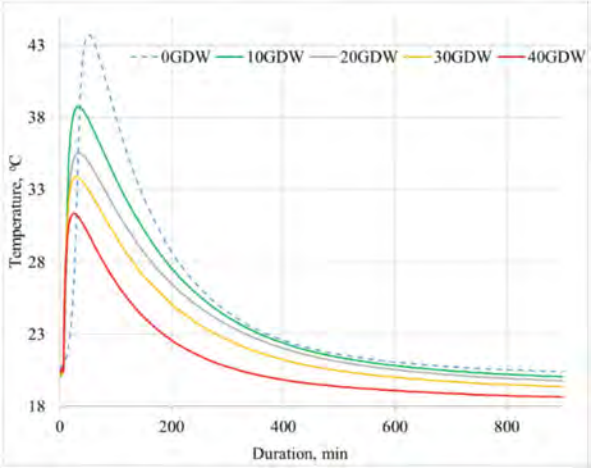


Fig. 4. Hydration temperature of gypsum composites samples.

The reference sample (0GDW) exhibits the highest temperature (43.6 °C), reflecting the typical exothermic behavior of pure building gypsum during setting. As the GDW content increases, the peak hydration temperature gradually decreases, with the 40GDW mixture reaching only 31.25 °C, and the temperature curve becomes more attenuated. This reduction in hydration temperature indicates a lower amount of gypsum binder. The duration of the main hydration peaks is also closely linked to the proportion of GDW in the mixture. As the GDW content increases, the hydration peaks shift toward shorter durations, which may be attributed to the accelerating effect of calcium sulfate dihydrate, as this phase acts as a setting accelerator within the system [11].

The density curve (Fig. 5a) shows that the sample with lowest amount of GDW exhibits the highest density (1389 kg/m^3), while higher amount of GDW leads to a gradual reduction, reflecting the lower density and more porous nature of samples.

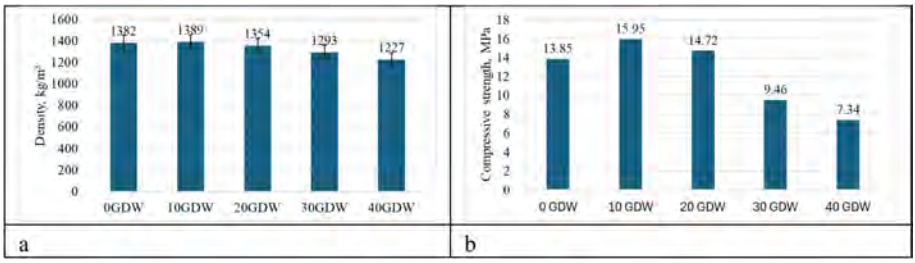


Fig. 5. The influence of the amount of GDW on the density and compressive strength of gypsum composites samples.

A similar trend is observed in the compressive strength results (Fig. 5b). The 10GDW sample achieves the highest strength (15.95 MPa), whereas mixtures containing 30–40% GDW show a noticeable decrease in mechanical performance. This reduction is associated with the diminished amount of reactive gypsum binder at higher substitution levels, which weakens the overall microstructure. The slight strength increase observed at 10% GDW can be attributed to a micro-filler and nucleation effect. At low replacement levels, fine GDW particles fill voids within the matrix and provide additional nucleation sites for gypsum crystallization, promoting a denser and more interconnected crystal network. This leads to improved mechanical performance compared with the reference sample. However, once the GDW content exceeds this optimal threshold, the reduced binder fraction and the more heterogeneous nature of the recycled material dominate, resulting in lower strength.

Despite these reductions, the composites containing moderate GDW levels (10%) retain sufficient strength for non-structural applications, highlighting the potential of GDW as a sustainable partial replacement in gypsum-based materials.

XRD analysis was used to determine the mineral composition of the hardened gypsum composites (Fig. 6). The results demonstrated that the mineral composition was nearly identical across all examined samples. Gypsum dihydrate (G) remained the dominant crystalline phase in all mixtures. Dolomite (D) and quartz (Q) were identified as minor phases originating from the GDW and BG. Although these phases do not participate in hydration, their presence contributes to the overall heterogeneity of the system and may influence mechanical performance by acting as non-reactive fillers. Bassanite (B) was also detected in small quantities.

The SEM images in Fig. 6 reveal a microstructure typical of gypsum dihydrate for the composite containing 10 wt% GDW. The material displays a dense and well-interlocked network of acicular gypsum crystals, characteristic of a fully hydrated and structurally cohesive matrix [12]. These needle-like crystals form continuous contact points, which explains the relatively high mechanical strength observed in samples with low GDW content. Overall, the SEM analysis confirms that low GDW additions can still

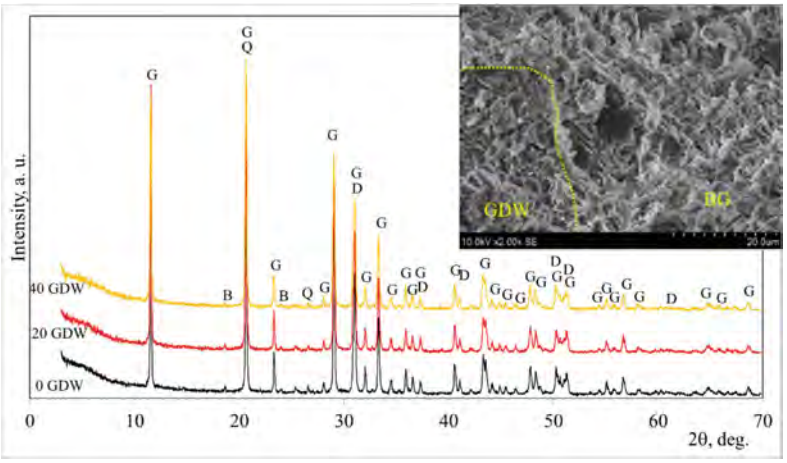


Fig. 6. Mineral composition according to XRD analysis and microstructure (SEM analysis) of gypsum composites samples. Notes: G - gypsum $CaSO_4 \cdot 2H_2O$ (33–331), B - basanite $CaSO_4 \cdot 0.5H_2O$ (33–310), D - dolomite $CaMg(CO_3)_2$ (74–1687), Q - quartz SiO_2 (72–916).

support the formation of a coherent gypsum matrix, directly influencing the mechanical performance of the composites. The contact zone between the GDW particles and the BG matrix shows the interface remains relatively well integrated, with gypsum dihydrate crystals growing around and partially anchoring the GDW fragments.

4 Conclusions

This study showed that gypsum demolition waste (GDW) can be effectively used as a partial replacement for building gypsum (BG), supporting more sustainable gypsum-based materials. Increasing GDW content reduced hydration-peak temperature and duration due to the lower binder fraction and the accelerating influence of residual calcium sulfate dihydrate. Up to 10 wt% of GDW improved compressive strength through micro-filler and nucleation effects, while higher levels (30–40 wt%) decreased density and strength because of reduced binder content and greater heterogeneity.

XRD confirmed a consistent mineral composition dominated by gypsum dihydrate, with dolomite and quartz from GDW acting as inert fillers. SEM analysis showed a dense, well-interlocked crystal network at low GDW levels and a more heterogeneous structure at higher substitutions. Overall, GDW is a viable and environmentally beneficial component for gypsum composites, particularly at low replacement levels suitable for non-structural applications, supporting circular-economy practices in gypsum-based construction. From a circular economy perspective, the use of gypsum-based demolition waste (GDW) as a partial replacement for building gypsum contributes to reducing construction waste and lowering the demand for primary raw materials. This approach supports material reuse within a closed-loop system and minimizes landfill disposal.

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Characterization of Ceramic Brick and Metakaolin Waste Geopolymers as Alternative to Portland-Cement Mortar

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Abstract. The valorization of construction and demolition waste (CDW) is a significant precondition of establishing sustainable and circular economy (CE). This study investigates the use of ceramic brick waste (CBW) and metakaolin waste (MKW) as precursors in geopolymer mortar systems as sustainable alternatives to conventional Portland cement-based materials. Experimental investigations evaluated the mechanical performance, microstructural development, and thermal resistance of CBW–MKW geopolymer mixtures. The developed geopolymer mortars demonstrated strong early-age performance (compressive strength) and formed a dense N–A–S–H gel matrix during curing. Exposure to 900 °C resulted in microstructural degradation in all mixtures; however, the mortar composition with the CBW–MKW ratio 1/1 (S2) retained the highest residual compressive strength and preserved the most coherent matrix structure. The results highlight that combining crystalline CBW with amorphous MKW improves thermal resistance and mechanical stability. The findings support the potential of CBW–MKW geopolymers as sustainable construction materials that can significantly contribute to CE and construction in the Baltic region.

Keywords: Valorization · ceramic brick waste · metakaolin waste · geopolymer mortar · alternative to Portland cement

1 Introduction

Construction and demolition waste (CDW) stands for one of the largest waste stream in the European Union (EU) and constitutes a significant share of total waste generation in the Baltic States. In Estonia, Latvia, and Lithuania, mineral construction waste (i.e. concrete, bricks, ceramics, and asphalt) forms the dominant fraction of CDW streams. Despite improvements in waste management systems and increasing recycling rates, a

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considerable percentage of these materials is still down-cycled into low-value aggregates or used for backfilling purposes. This means that circular economy high-value recycling pathways remain underdeveloped. Therefore, innovative material solutions capable of transforming mineral construction waste into new construction materials, such as geopolymer binders, represent an important opportunity to increase material circularity and reduce reliance on virgin resources across the Baltic region [1, 2]. CDW represents a relevant secondary resource for the Baltic construction sector. A significant share of buildings constructed during the twentieth century in Estonia (e.g. largest share, 35.4% of the Estonian Building Stock [3]), Latvia, and Lithuania utilized ceramic brick masonry structures. Ongoing demolition, but also reconstruction of these aging building stocks generates substantial quantities of CBW.

In recent years, geopolymer materials have gained increasing attention as sustainable alternatives to Portland cement due to their lower environmental footprint, reduced CO_2 emissions, and favorable mechanical and durability properties. The growing emphasis on circular economic principles has further encouraged the use of secondary raw materials, enabling the development of greener construction products without compromising performance. In this context, industrial waste–derived aluminosilicate precursors have become particularly relevant for producing geopolymer binders. Ceramic brick waste (CBW) waste has found to be valuable, sustainable resource that can be repurposed in construction industrial applications, [4, 5] where it can be recycled as an aggregate substitute in concrete, an asphalt additive, or a supplementary cementitious material when ground into powder. Metakaolin waste (MKW) is a high-activity, silica- and alumina-rich byproduct primarily generated during industrial processes like expanded glass manufacturing. It is increasingly utilized in construction as a sustainable additive to enhance the mechanical properties, density, and durability of high-performance and geopolymer concretes [6–8]. Phosphogypsum (PG) is a solid waste product that is generated in the phosphoric acid manufacturing process, most of which is currently sent to landfills rather than recycled [9].

Previous studies [10–12] have established that a ternary alkali-activated binder system formulated from CBW, MKW, and PG forms a dense gel matrix and significantly improves mechanical properties. Low-calcium geopolymers cured under ambient conditions achieve good strength due to the uniform formation of Sodium Aluminosilicate hydrate, i.e. N-A-S-H gel. An optimal Na_2SiO_3/NaOH ratio results in a denser matrix and higher compressive strength of the geopolymers. Geopolymers also exhibit significantly better high temperature resistance (up to 1000–1200 °C) compared with cementitious binders, whose microstructure begins to degrade at around 400 °C due to $Ca(OH)_2$ decomposition, and which may lose up to 95% of their strength at 1000 °C. Their thermal stability is attributed to a dense inorganic matrix and a lower susceptibility to moisture induced damage [13].

Although CBW and MKW have been extensively investigated as precursors in geopolymer systems, limited research exists on the high temperature behavior of their combined CBW–MKW systems. Therefore, the present study aims to evaluate the strength and microstructural transformations of the CBW–MKW geopolymer mortar before and after heating, with the goal of understanding the relationship between thermal resistance. The aim of the study is also supported by the fact that in urgent need

for transition to CE, innovative material technologies that enable the valorization of secondary mineral resources can significantly reduce environmental impacts associated with traditional construction materials [1].

2 Materials and Methods

2.1 Composition of Geopolymer Mortar

The geopolymer binder was produced from CBW and MKW, both finely milled aluminosilicate precursors with comparable particle sizes (~11–13 μm) and high fineness. CBW is quartz rich and predominantly crystalline, while MKW contains a high amorphous fraction and elevated Na_2O due to residual glass. Phosphogypsum (PG), was added at a constant 5 wt% as a calcium source, promoting accelerated geopolymerization. Three precursor blends (Table 1) were activated using soluble glass (SG) and 10 M NaOH solution (SH) at SG/SH ratios of 1.0. To evaluate the effect of natural sand aggregate on the mortar, three different binders to aggregate ratios were used: 2/1, 1/1, and 0.5/1. The geopolymer mortar was mixed using an electric mixer, with the alkaline activators premixed beforehand.

Table 1. Composition for geopolymer mortar samples, wt%.

Sample	Precursor (P), wt%			AA/P ratio	Sand/P ratio
	CBW	MKW	PG		
S1 1:2	47.5	47.5	5	0.55	2
S1 1:1	47.5	47.5	5	0.55	1
S1 2:1	47.5	47.5	5	0.55	0.5
S2 1:2	22.5	72.5	5	0.65	2
S2 1:1	22.5	72.5	5	0.65	1
S2 2:1	22.5	72.5	5	0.65	0.5
S3 1:2	0.0	95.0	5	0.75	2
S3 1:1	0.0	95.0	5	0.75	1
S3 2:1	0.0	95.0	5	0.75	0.5

2.2 Preparation, Curing, Heating, Cooling and Compressive Testing of Geopolymer Mortar Samples

The prepared geopolymer mortar was then cast into cubic molds (40 mm × 40 mm × 40 mm), compacted on a vibrating table, and covered with a film to prevent moisture loss (Fig. 1a).



a b

Fig. 1. Comparison of geopolymer mortar prior to heating (a) and after thermal exposure at 900 °C (b).

Altogether, 36 geopolymer samples were prepared. Each value represents the mean of three samples ± standard deviation. The samples were cured for 24 h under ambient conditions (20 ± 2 °C, 45% RH) removed from molds, and subsequently oven cured at 60 °C for 24 h to enhance early strength. Further curing continued for 3, 7, and 14 days, after which compressive tests were performed for geopolymer samples. The high-temperature regime was applied using a constant heating rate method, increasing the temperature at 5 °C/min up to 900 °C. The target temperature was held for 2 h. After heating, nine samples were allowed to cool naturally inside the furnace, and the residual compressive strength was subsequently determined.

Scanning electron micrograph (SEM) images were taken and prepared to illustrate the microstructure and, thus, to evaluate the performance of geopolymer mortar in elevated temperature (900 °C) conditions.

3 Results and Discussion

3.1 Compressive Strength of Geopolymer Mortar

The compressive strengths of geopolymer samples of three precursor ratios (1/2;1/1, 2/1) times three binder to aggregate ratios (CBW/MKW) were compared at the age of 3, 7 and 14 days (Fig. 2). After 3 days, the geopolymer mortar typically reached a significant initial compressive strength (38.5 MPa on average, ranging from 26.0 to 43.1 MPa), as alkaline activation reactions proceeded intensively and N–A–S–H gel formed rapidly. At this stage, most of the early binding products that determine the structure of the matrix were generated. After 7 days, the compressive strength (39.1 MPa on average, ranging from 28.8 to 45.3 MPa) continued to increase as the reaction products became denser, the porosity of the samples decreased, and the gel matrix stabilized. By this time, geopolymers usually achieve about 70–85% of their final strength. After 14 days, the compressive strength increased further (59.1 MPa on average, ranging from 32.9 to 60.4 MPa), although in some precursor and binder to aggregate ratios the reactions approached equilibrium as the microstructure became denser and more consolidated. At this point, the geopolymer mortar typically reached a nearly stable (final) strength, which, however, could be verified at the age of 28 days.

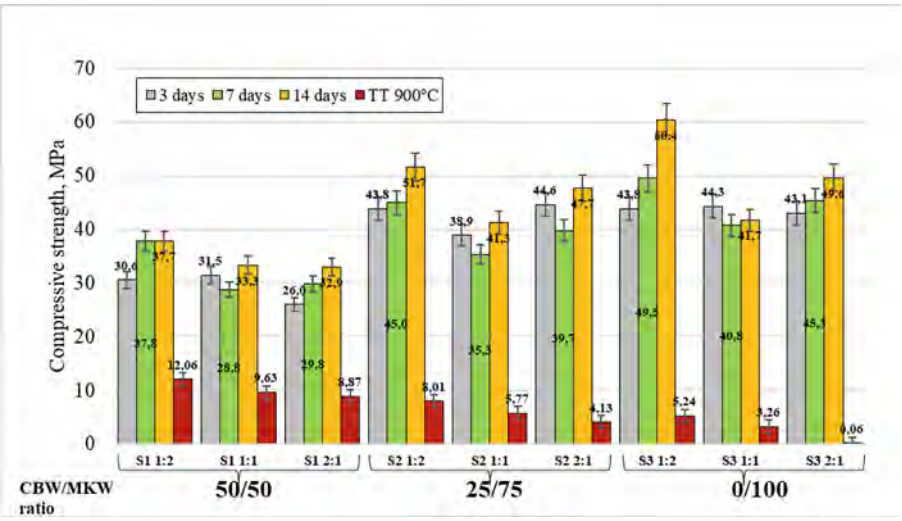


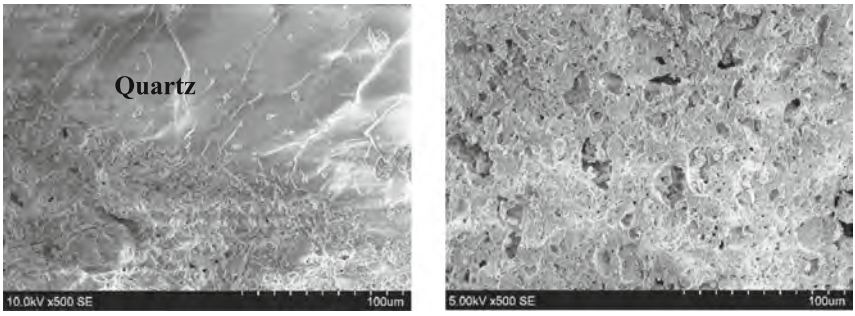
Fig. 2. Compressive strength of geopolymer mortar samples prior to and following an exposure to 900 °C. The sample types are listed in Table 1.

3.2 Residual Compressive Strength of Geopolymer Mortar at Elevated Temperature

To evaluate the effect of high temperature, compressive strength values before and after thermal treatment were compared. Figure 2 shows a pronounced reduction in compressive strength after exposure to 900 °C. The initial samples exhibited higher strength due to a continuous gel matrix, but high temperature caused microstructural degradation, increased porosity, and the formation of microcracks, resulting in a significant loss of residual strength. This confirms that extreme heating critically affects the structural integrity of the geopolymer binder. The optimal mixture was the one that achieved the highest compressive strength before heating and retained the greatest residual strength after exposure to 900 °C, meaning it experienced the smallest loss of mechanical properties. The optimal mixture was the one that maintained both mechanical strength and structural integrity after exposure to 900 °C. While the S3 mixtures developed the highest early compressive strength due to their high metakaolin content, their dense and brittle matrix led to severe cracking after thermal treatment (Fig. 1b). In contrast, the S2 series—combining MKW with CBW - showed significantly better thermal stability. Among them, the S2 1:1 composition provided the most balanced performance: it achieved sufficient initial strength and retained the highest residual strength without structural failure after heating. This indicates that the combination of MKW and CBW, together with a moderate sand-to-precursor ratio, produced a geopolymer matrix capable of withstanding extreme thermal stress more effectively than the other tested formulations.

3.3 Impact of Elevated Temperature on the Microstructure of Geopolymer Mortar

SEM images in Fig. 3 illustrate the microstructural evolution of the S2 1:1 geopolymer mortar before and after exposure to 900 °C, highlighting the changes responsible for its mechanical behavior. In the unheated state (Fig. 3a), the mortar matrix appears dense and well-consolidated, with a continuous N–A–S–H gel phase binding the precursor particles and filling the pore spaces. The microstructure shows limited cracking and a uniform distribution of reaction products, which corresponds to the good initial compressive strength observed for this mortar.



a b

Fig. 3. SEM images of S2 1:1 geopolymer mortar prior to (a) and following exposure to 900 °C (b).

After thermal exposure (Fig. 3b), noticeable microstructural degradation becomes evident: microcracks propagate throughout the matrix, the gel phase shows signs of shrinkage and partial decomposition, and the overall structure becomes more porous. Despite these changes, the S2 1:1 sample retains a more coherent matrix compared with other formulations, indicating that the combined CBW–MKW precursor system provides improved thermal stability. This microstructural resilience explains why S2 1:1 maintained the highest residual strength after heating and was identified as the most thermally resistant mixture in the study. From CE angle, the use of CBW–MKW in geopolymer binders can be interpreted as a form of industrial symbiosis, where waste streams from one process are utilized as inputs for another [14]. In the Baltic States, collaboration between demolition companies, waste sorting facilities and construction material producers could facilitate the recovery and valorization of mineral waste streams, support local resilience and regional supply chains, while reducing landfill disposal and the demand for virgin resources.

4 Conclusions

The study demonstrated that CBW–MKW–PG–based geopolymers can be successfully produced using industrial waste precursors and that their mechanical and thermal performance strongly depends on the precursor ratio and aggregate content. All mixtures

developed substantial early strength due to rapid N–A–S–H gel formation, reaching near final strength within 14 days. However, exposure to 900 °C caused significant degradation of the gel matrix, increased porosity, and microcracking, resulting in a notable reduction in compressive strength. Among the tested formulations, the S3 mixtures, despite their high initial strength, exhibited severe cracking after heating due to their dense and brittle MKW rich matrix. In contrast, the S2 series, which combined MKW with CBW, showed markedly better thermal stability. The S2 1:1 composition proved to be the most resilient, retaining the highest residual strength and preserving a more coherent microstructure after heating. These findings indicate that incorporating both crystalline CBW and amorphous MKW, together with a balanced sand to precursor ratio, enhances the thermal resistance of geopolymer mortar. Overall, the results highlight the potential of CBW–MKW-based geopolymers as sustainable, thermally stable construction materials and underscore the importance of precursor synergy in optimizing high-temperature performance. The results of this research highlight that CBW–MKW can serve as promising precursors for geopolymer binders, contributing to more circular material use in the construction sector. From a circular economic perspective, the valorization of such mineral waste streams could be further supported through industrial symbiosis between demolition companies, waste sorting facilities and construction material manufacturers. However, wider implementation in the Baltic States may be constrained by limited economic incentives and fragmented institutional coordination. Policy instruments such as green public procurement, improved material traceability and the development of technical standards for secondary construction materials could help accelerate the transition toward circular construction systems in the region.

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Sequestration of CO_2 in Prefabricated Interlocking Concrete Pavements with Fly Ash

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Abstract. Reducing GHG emissions from the global construction sector is critical. While cement is a source of greenhouse gas emissions, cement-based construction material sequesters CO_2 through carbonation. Examining methods and materials for CO_2 sequestration that can act as partial substitutes for cement in concrete will continue to sequester CO_2, in addition to reducing cement demand in concrete. Concrete pavers with different fly ash contents were produced to evaluate the carbon sequestration capacity of interlocking concrete pavers in this study. Pre-manufactured interlocking concrete paving stones were produced with 0%, 15%, and 30% fly ash added, and the samples were examined over 1 and 5 days. The results clearly showed that the increase in mass after 5 days was higher than that after 24 h for all levels of fly ash content. The most effective fly ash content for CO_2 sequestration in these pavers is 30%. Based on these findings, the use of fly ash-containing prefabricated interlocking concrete pavers is recommended for CO_2 sequestration.

Keywords: Concrete Carbonation · Fly Ash · Interlocking Concrete Pavers · Embodied CO_2

1 Introduction

Alternative methods for reducing carbon dioxide (CO_2) emissions in the atmosphere are being explored, and more approaches should be developed. Carbon emission analysis of construction sectors can provide critical information to identify opportunities and provide tailored solutions to reduce GHG emissions from global construction. Carbonation of cementitious materials has the dual benefit of sequestering CO_2 and reducing emissions by reducing the need for cement in concrete utilizing recycled material for carbonization. Additionally, the concrete life cycle should be presented, and the embedded CO_2 values should be determined. CO_2 capture methods to accelerate carbon sequestration in concrete and carbon footprint-reducing materials that can be used as partial substitutes for cement in concrete should be analyzed [1]. The development of carbon capture and reduction methods is essential. Concrete with different fly ash ratios was

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produced in this study to assess the carbon capture ability of the interlocking concrete pavement products. The fly ash was added to the prefabricated interlocking concrete pavement in 0%, 15%, and 30% were examined for 1 and 5 days. The figures clearly show that the mass rise is higher after 5 days than after 24 h for all fly ash ratios. The most effective CO_2 capture percentage for fly ash-containing pavements is 30%. According to the obtained results, a prefabricated interlocking concrete pavement with a fly ash ingredient is recommended to capture CO_2.

2 Methodology

2.1 Materials

Aggregates

Crushed sand with a size range of 0–4 mm and crushed stone aggregates with a size range of 4–11 mm were used in the production of paving stones. The characteristic properties of the aggregates utilized are listed in Table 1.

Table 1. Characteristic properties of aggregates.

Aggregate	Water absorption (%)	Specific gravity (gr/cm^3)	Abrasion (%) (Los Angeles)
0–4 Crashed-sand	1.71	2.35	–
4–11 Crashed-stone	0.94	2.69	26.16

Binders

CEM I 42.5 R Portland cement and Seyitömer fly ash were used as the binding materials. The cement has a specific gravity of 3.10 and a Blaine fineness of 3600 cm^2/g. The fly ash generated by the combustion of lignite coal at the Seyitömer Thermal Power Plant in Kütahya is a low-calcium (Class F) artificial pozzolanic material. It has high recovery potential in the construction sector for applications such as enhancing concrete durability, serving as a cement additive, and brick production [10]. The specific gravity of the fly ash from the Seyitömer thermal power plant is 2.13. The oxide values obtained from the chemical analysis of the two materials are shown in Table 2.

2.2 Mixing Ratios and Experiments Conducted

Aggregates were designed for particle production using a mixture of 50% crushed sand and 50% crush stone. The water-to-binder ratio in the mixtures remained constant at 0.56. The binder content remained constant at 270 kg/m^3. First control series were produced by mixing crushed sand with crushed stone aggregates. Cement was replaced by fly ash at rates of 0%, 15%, and 30% of the cement weight. Zero-slump concrete was used in the production of interlocking pavers, as it allows for the production of very dry concrete—where the water-to-cement ratio is kept to a minimum—that is suitable for compaction via pressing and vibration and can be removed from the mold immediately.

Table 2. Chemical analysis results for CEM I 42.5 Portland cement and Seyitömer fly ash.

Chemical component	Cement (%)	Fly ash (%)
CaO	64.25	0.67
SiO_2	19.7	46.51
Al_2O_3	5.65	25.47
Fe_2O_3	4.05	4.88
MgO	0.91	5.94
SO_3	2.65	1.7
K_2O	0.77	1.35
Na_2O	0.17	0.36
K.K.	1.07	2.78

The interlocking pavers produced as part of the experimental studies were 80-mm-thick. Pavers were produced at Kumcuoğlu (Yeşilay) Construction, a paver manufacturing company based in Afyonkarahisar. The planks were treated by spraying water onto them for the initial 3 days following their production. The samples were then left to stand under normal atmospheric conditions until the day of testing. Tests for compressive strength, splitting tensile strength, and abrasion resistance were conducted on the planks on days 3, 7, and 28.

Tests for water absorption, apparent porosity, and density were conducted on 28-day-old samples in accordance with Archimedes' principle. The compressive strengths were determined using a fully automatic 200-ton press. The tensile strengths were determined in accordance with the Brazilian method and the TS 2809 EN 1342 standard [2]. The abrasion tests were also conducted in an abrasion machine according to the method outlined in Annex G of the same standard. The abrasion disk was rotated at 75 rpm, while the abrasion powder was flowed at a rate of 2.5 m/s. The flow rate between the sample and the disk, placed vertically in the machine, is measured in liters per minute.

The thickness of the area abraded by the disc on the specimens was determined by taking three measurements at different points with a precision of 0.01 mm. Then, the average of these values was calculated. Compression and wear tests were conducted on the three samples. Tensile strength test results on six samples were averaged using the arithmetic mean.

2.3 Carbonation Experiment

The concrete specimens were subjected to an accelerated carbonation test using a sealed carbonation container after the curing process, as shown in Fig. 1. The relative humidity was maintained at 55% throughout the carbonation test. A saturated sodium dichromate solution was prepared and placed at the bottom of the carbonation chamber to maintain a humidity of 55% inside the sealed container. The carbonation test specimens were placed inside the test chamber, and the chamber lid was tightly sealed to ensure airtightness. CO_2 gas was introduced in a controlled manner by simultaneously reading the pressure

gauges on the CO_2 cylinder and carbonation chamber. In the experiment, the specimens were exposed to 40% CO_2 at 1- and 5-day intervals.



Fig. 1. Rapid carbonation test setup.

On each test day, 100-mm cubes were subjected to a splitting test to determine the concrete carbonation depth. The carbonation depths were determined by spraying phenolphthalein onto the inner surfaces of the concrete specimens using the method recommended by RILEM CPC18 [11] (Fig. 2). The phenolphthalein solution was sprayed onto the concrete surface, which was cleaned of dust and particles. Phenolphthalein is an acid indicator that turns pink when the pH exceeds 9, i.e., when the concrete is alkaline. If no color change occurs, carbonation has occurred, and the depth of the carbonated surface layer can be measured. The values reported for carbonation depth are the average of eight measurements taken on the surface of the split concrete cube.

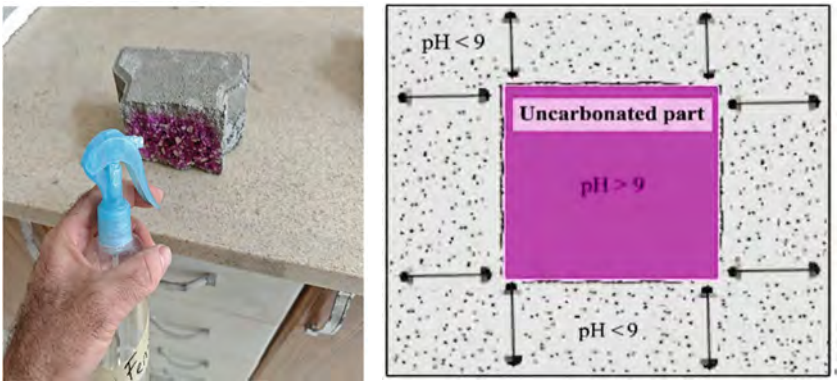


Fig. 2. Determination of the depth of carbonation on the fractured surface of concrete [12].

3 Experimental Results and Discussion

3.1 Compressive Strengths

The compressive strengths of the interlocking paving stones produced using crushed stone aggregates are shown in Fig. 3. The compressive strength of the produced pavers increases with the curing time of the samples. While the increase in strength occurs in a regular manner in pavers with fly ash contents of 0% and 15%, a relative decrease in strength is observed in pavers containing high fly ash contents, such as 30%. During the hardening of cement-based composites, CaO and other silicate components present in the cement undergo chemical reactions to form calcium silicate hydrates (C-S-H) and calcium hydroxide ($Ca(OH)_2$) [3]. The calcium hydroxide released in this study reacted with the silicates from the fly ash to form new C-S-H products, thereby increasing the concrete's density and early-age strength. As the proportion of fine material in the flooring increased, the compressive strength values decreased due to the increased water requirement and the reduction in the amount of free lime necessary for binding silica [3–7].

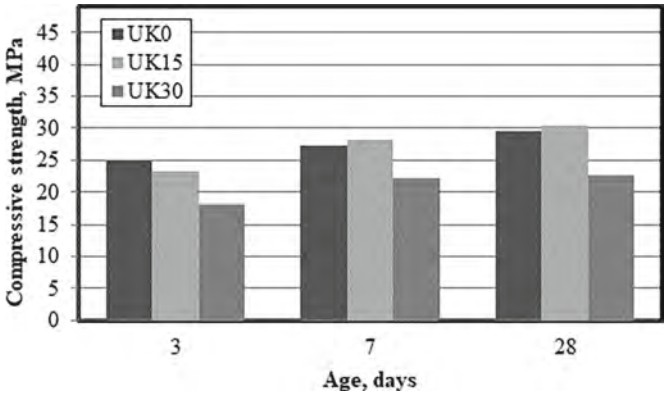


Fig. 3. Variation in compressive strength of interlocking pavers as a function of fly ash (UK) content.

3.2 Tensile Strength

Paving stones must meet a splitting tensile strength of 3.6 MPa to be in accordance with the standard for paving stones (TS 2809 EN 1342) [2]. Consequently, this value is of great significance for paving stone manufacturers as it enables the stones to be brought to market promptly without occupying excessive storage space. The splitting tensile strength is defined according to the standard, with its average values illustrated in Fig. 4.

The interlocking pavers' 3- and 7-day strengths were obtained from the samples without fly ash. However, the limit value could not be reached because the fly ash exhibited its pozzolanic activity at later ages because the cement was partially replaced with fly ash at specific ratios. The limit strength value was exceeded after only 28 days.

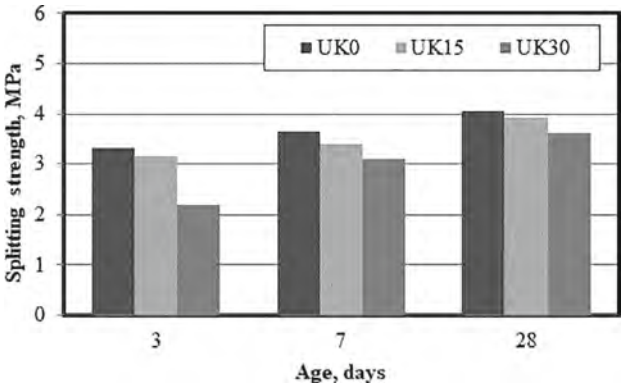


Fig. 4. Variation in splitting strength of pavers produced with crushed stone aggregate as a function of fly ash (UK) content.

Considering the strength values at early ages, the use of fly ash in paving stone production may not seem very suitable for paving stone manufacturers at first glance. However, this problem can be solved using methods such as accelerated curing. No significant strength loss was observed when 10% fly ash was used. Similar results were observed by Durmuş and Şimşek [6]. The greatest difference in the strength of 3-day-old paving stones with a 20% fly ash content was 0.5 MPa when examining the effect of aggregate on the tensile strength of interlocking paving stones.

3.3 Carbonation

After the cement-bound interlocking pavers were subjected to accelerated carbonation, the paver samples were split open, and the areas containing CO_2 reacted with the phenol solution, turning pink. A phenolphthalein solution is applied to the concrete surface in this test. Phenolphthalein is colorless in uncarbonated concrete under alkaline conditions but exhibits a pink-to-purple color change in carbonated areas. Thus, the carbonation depth can be determined by the color change of the phenolphthalein reagent applied to the concrete surface [8]. The concrete samples left in the carbonation tank for 1, and 5 days progressed from dark to light. Calcium carbonate ions formed as a result of carbonation lower the pH [9]. Light pink tones were observed in areas with high pH when the phenolphthalein solution was sprayed (Fig. 2).

When the average carbonation depth in the concrete specimens produced following the accelerated carbonation test was measured, it was 1.9 mm after 1 day and continued to increase, reaching a depth of 3.1 mm after 5 days (Fig. 5). As the carbonation depth increases, carbonation capture percentage increases.

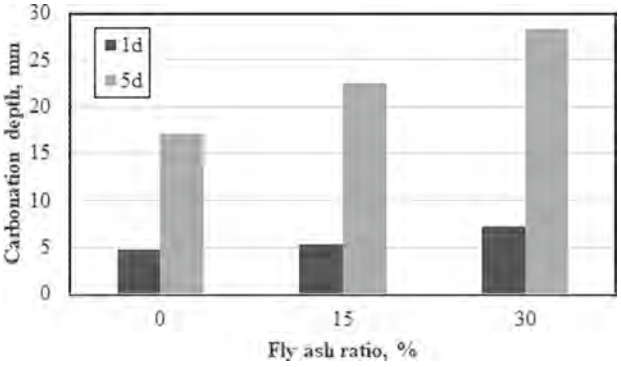
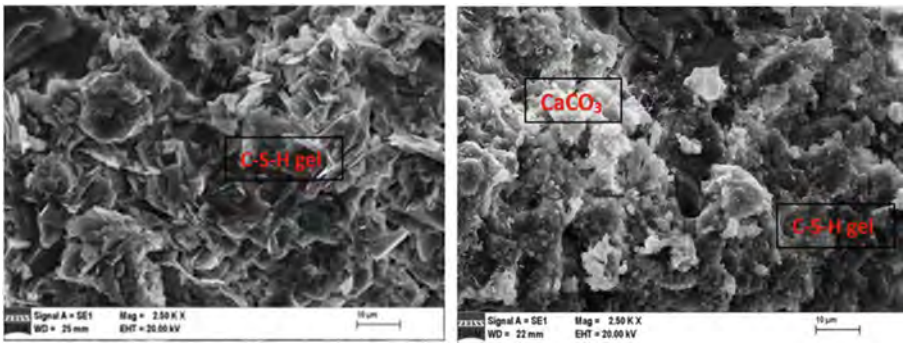


Fig. 5. Carbonation depths of interlocking pavers.

3.4 Microstructure

As shown in Fig. 6a, the hydration products in the cement-based composites consist predominantly of C-S-H gels. During carbonation, CO_2 from the air penetrates the composite through pores, capturing the free CaO products in the internal structure and converting them into $CaCO_3$, as illustrated in Fig. 6b), where the carbonation process takes place. As the penetration depth of CO_2 into the composite increases, the hydration products become more carbonated.



(a) (b)

Fig. 6. SEM image of carbonation products in interlocking pavers.

4 Conclusions and Recommendations

This study investigated the use of fly ash—an industrial waste material—in the production of interlocking pavers and its associated carbon sequestration performance. The incorporation of fly ash in paver manufacturing led to a rise in strength at later stages of up to 10–20%. Further increases the fly ash content resulted in decreased strengths.

Fly ash has shown a similar effect on tensile strength to that observed in compressive strength.

The use of fly ash waste in paving stone production will result in substantial economic advantages. Furthermore, waste materials discarded into the environment will be eliminated, and environmental damage will be prevented by using them as recycled materials. Fly ash, another waste material, can be incorporated at rates of 10% to 20% through specialized production methods, enabling the production of paving stones with smoother surfaces and superior performance.

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Use of Pre-carbonated Recycled Aggregates to Reduce the Environmental Footprint of Constructions - Approach Through LCA and Study of Application Limits

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Abstract. Construction and demolition waste constitutes approximately 1/3 of solid waste worldwide with serious technical, economic and regulatory problems during their recovery and reuse in construction. A substantial proportion of this waste stream consists of concrete, which may be reutilized as recycled aggregates in new construction applications. However, in addition to the challenges, the overall environmental benefit remains uncertain because of the impacts associated with processing and transportation. In this work, the environmental impact is investigated when the percentage of aggregate replacement by recycled concrete increases, taking data from a real unit and application case in Greece. The possibility that the recycled aggregates have been pre-carbonated (using exhaust gases from a neighboring cement factory rich in CO_2 emissions), as well as the parameter of transport distance is also examined. The results quantitatively highlight the environmental benefit of using recycled aggregates in concrete, which becomes considerably more significant when they have been pre-carbonated. However, when the distances of their transport to the unit of use exceed a certain limit, then the environmental benefits are zeroed and then reversed. It is therefore necessary that any use of recycled material or related practice goes through strict control, e.g. through an LCA, in order to finally quantify the environmental benefit and the sustainability of the construction, but also to investigate the limits beyond which there may be additional environmental costs as compared to conventional practice.

Keywords: Carbonation · Life Cycle Assessment (LCA) · Recycled Concrete Aggregates (RCAs) · Sustainability · Transportation

1 Introduction

The last decades, the accelerated urbanization led to the generation of large amount of construction and demolition waste (CDW) [1] that contributes to approximately 35% of the overall global waste. CDW consists of discarded materials produced during construction, renovation/retrofitting and demolition works. These wastes are heavy and they are the bulkiest waste generated all over the world which makes them difficult to handle

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[2]. Concrete waste represents the largest proportion (60–70%) of CDW, and it is anticipated its amount to reach 7,750 million tons by 2050 [3]. The improper processing and disposal of CDW results in severe environmental impacts such as higher CO_2 emissions and natural resource depletion [4].

High efficiency in terms of environmental and economic gains is represented by the recycling of CDW to replace natural aggregates (NAs) in production of concrete [5]. A lot of research has been published that compares the environmental imprints of production of NAs and recycled concrete aggregates (RCAs) through life cycle assessment (LCA). The usefulness of LCA lies in the determination and comparison of impacts to make decisions that will affect the entire life cycle of any building or infrastructure project [6]. According to literature, the production of RCAs from CDW, compared to NAs, reduces the greenhouse gases (GHG) emissions as Global warming potential by 60–65%, minimizes the SO_2 equivalent emissions as Acidification Potential by 40–50% and saves up to 50–60% of non-renewable energy [2].

However, the workability, mechanical performance and durability of RCAs are always inferior to that of NAs (e.g. RCAs present higher crush value, lower density) and thus the addition and the application fields of RCAs are strictly limited [7]. The properties of RCAs can be enhanced with accelerated carbonation which is a promising technology that contributes also to mitigating global warming [1]. Accelerated carbonation is based on chemical reactions between hydrated products and unhydrated cement minerals in RCAs and CO_2 [8]. Calcium carbonate that is generated during the carbonation process precipitates in the pores and cracks of RCAs, which can refine the microstructures of RCAs and improve their quality. In addition, accelerated carbonation can lead to permanent absorption of CO_2 in the RCAs without bringing second environmental pollution, such as fine aggregates and wastewater [1]. According to Leemann et al. [9] by using carbonated RCAs, CO_2 absorption of up to 21.2 kg per ton of RCA can be achieved.

Another very important parameter that should be taken into account during waste management is waste transport because transporting bulky CDW is one of the major contributors to GHG emissions and contributes also to a high economic impact. The transportation needs of a recycling facility account for almost 54% of total CO_2 equivalent emissions [2]. In this study, the environmental impact is investigated when the percentage of aggregate replacement by RCAs increases, taking data from a real unit and application case in Greece. The parameter of transport distance is also examined, as well as the possibility that the RCAs have been pre-carbonated (using exhaust gases from a neighboring cement factory rich in CO_2 emissions).

2 LCA Methodology

LCA is employed for evaluating, qualitatively and quantitatively, the potential environmental impacts of a product or system, the consumption of natural resources and the energy in the entire life cycle of the product or system [2, 10]. The most widespread standards for LCA approach are ISO 14040:2006 and ISO 14044:2006, which define four major stages to perform LCA: goal and scope definition, life cycle inventory (LCI), impact assessment (LCIA), and interpretation [1, 11].

2.1 Goal and Scope Definition

The main objective of this study is the investigation of the environmental impact when the percentage of aggregate replacement- mainly of gravel and sand- by RCAs increases in concrete as well as the possibility that the RCAs are pre-carbonated. Regarding the latter, the main variables considered were the percentage of replacement of NA with pre-carbonated RCAs (CRCA) and the transportation distances from the aggregate recycling unit that includes the transport of CDW to the recycling unit, the transport of RCA to the carbonization unit and the transport of CRCA to the construction site. Different replacement rates of NAs with RCAs and CRCA were evaluated to systematically assess how the substitution of conventional materials with recycled materials influences the environmental performance across varying levels of incorporation.

2.2 Methodology

The data that was used for the LCA analysis derived from the literature and the Ecoinvent database. The LCA was performed using SimaPro software. SimaPro is used for data aggregation, LCI, LCIA and sensitivity analysis of the results. Functional unit (FU) is used as a basis of comparison were all the parameters of inventory refer to it [12]. In the present study the FU is 1 m^3 of concrete. The stage that requires extreme caution is the LCI stage, where all the necessary data are gathered, and all the inputs and the outputs of the whole production system are calculated. The assessment of the potential impacts using the LCI data takes place at the LCIA stage [12]. ReCiPe2016 Hierarchist perspective is an LCIA methodology that was taken into consideration in the present study [13]. This methodology features a dual-level analytical framework comprising midpoint categories, encompassing three critical dimensions (endpoint categories): human health, ecosystem quality and resource scarcity. The three endpoint damage categories can be further normalized and aggregated by converting their units to Pt, that represents the average environmental burden a European citizen causes in the timespan of a year.

2.3 Aggregate Replacement by RCAs in Concrete Production

As mentioned above, this study aims to compare the environmental footprint of a typical concrete that contains NAs with a recycled concrete that contains high quantity of RCAs. Five scenarios were taken into account: S0 takes into consideration the production of standard concrete (0% RCAs in its composition), S1 concerns the production of concrete with 10% replacement of NAs with RCAs, S2 takes into account the production of concrete with 20% replacement of NAs with RCAs, in S3 the production of concrete includes 30% replacement of NAs with RCAs and finally in S4 the replacement of NAs from RCAs is 40%. The cement quantity and the water quantity considered for the production of 1 m^3 of concrete was 380 kg and 180 kg respectively, while the data regarding the energy required for the recycling of aggregates and the quantities of aggregates were extracted from a CDW facility located in Ilia prefecture (Western Greece). More details are presented in Table 1. The energy required for the manufacture of concrete is 2.5 kWh/m^3 (information extracted after communication with a concrete plant).

The facility treats approximately 80–100 m^3 of waste per day (up to 200 m^3/d depending on the material) which corresponds to an energy requirement of €70–80 per day. The price of the kilowatt-hour taken into account was €0.1482/kwh that means approximately 506 kwh/day for the total m^3 of waste treated. Therefore, for 1 m^3 of RCAs 5.62 kWh/m^3 are calculated. In addition, 1 m^3 of aggregates considered to be approximately 1346 kg of aggregates. This is how the required energy of the RCAs was calculated in Table 1, i.e. by converting the kg of RCAs to m^3 and then multiplying the m^3 amount with 5.62 kWh/m^3.

Table 1. Aggregate quantities and required energy for the recycling of the aggregates in the different Scenarios.

Concrete Scenario	NA (kg)	RCA (kg)	RCA (m3)	Energy (kWh)
S1	1584.9	176.1	0.1308	0.7352
S2	1408.8	352.2	0.2617	1.4705
S3	1232.7	528.2	0.3925	2.2058
S4	1056.6	704.4	0.5233	2.9411

2.4 Use of Pre-carbonated RCAs in Concrete Production

The main variables considered in the use of CRCA in concrete production regarding the calculation of the environmental impacts were the percentage of replacement of NA with CRCA and the transportation distances. Three scenarios were investigated. Scenario I takes into consideration the production of concrete with CRCA at replacement rates of 25%, 50%, 75% and 100% with the longest possible distance of the aggregate recycling unit (i.e.188.3 km). Scenario II concerns the production of concrete with CRCA at the same replacement rates as Scenario I with the shortest possible distance of the aggregate recycling unit (i.e. 68.1 km), and in Scenario III the same replacement rates were considered but the distance factor was ignored. In all three scenarios, the carbonation of the aggregates is carried out with gas emissions from a cement plant. The study is based on the relative distances of units in Achaia prefecture and the wider region of Western Greece. In this case, the entire range of aggregate replacement from 0–100% is examined (as opposed to the limited range of the previous case) in order to fully highlight any impact of carbonized recycled aggregates on environmental indicators.

The energy amount required for the integration of the data in the production of concrete with CRCA was based on conventional processes. Specifically, the energy required for the production of 1 m^3 of conventional concrete taken into consideration was 2.5 kWh/m^3/d, 4.1667 kWh/m^3/d for the production of recycled aggregates and 0.50688 kWh/m^3/d for the carbonation of RCA. The layout of the RCA carbonization equipment was based on the study of Torrenti et al. [14]. In more detail, it was assumed that a rotating chamber of 11 m length and 2 m radius was used. The rotary motion in combination with the lifters welded to the tube liners allow the contact of the aggregate surface with the gas fed into the cylinder. The data of the aforementioned processes are presented in Table 2.

Table 2. Input and output data for the production of 1 m^3 concrete.

1 m^3 concrete		Production of conventional concrete	Production of concrete with CRCA 25%	Production of concrete with CRCA 50%	Production of concrete with CRCA 75%	Production of concrete with CRCA 100%
Input	Cement kg/m^3	380	380	380	380	380
	Water kg/m^3	180	180	180	180	180
	NA kg/m^3	1761	1321	880.5	440	–
	CRCA kg/m^3	–	440	880.5	1321	1761
	Required energy kWh/d	2.5	3.0434	3.58679	4.130184	7.17358
	CO2 kg/m^3/d	270	271.32	272.64	273.96	275.283
Output	% carbon dioxide absorbed during carbonation	–	35.98	72	108.2	144

3 Results and Discussion

3.1 Aggregate Replacement by RCAs in Concrete Production

Through the ReCiPe2016, at the characterization step, the performance of the scenarios was evaluated across 18 midpoint environmental impact categories. The midpoint categories are further aggregated into three endpoint damage categories i.e. human health, ecosystem quality and resource scarcity (damage assessment step). In the normalization step, all scores displayed in the damage assessment are normalized using the impact of an average European per year. The normalized results for the 5 scenarios are presented in Fig. 1.

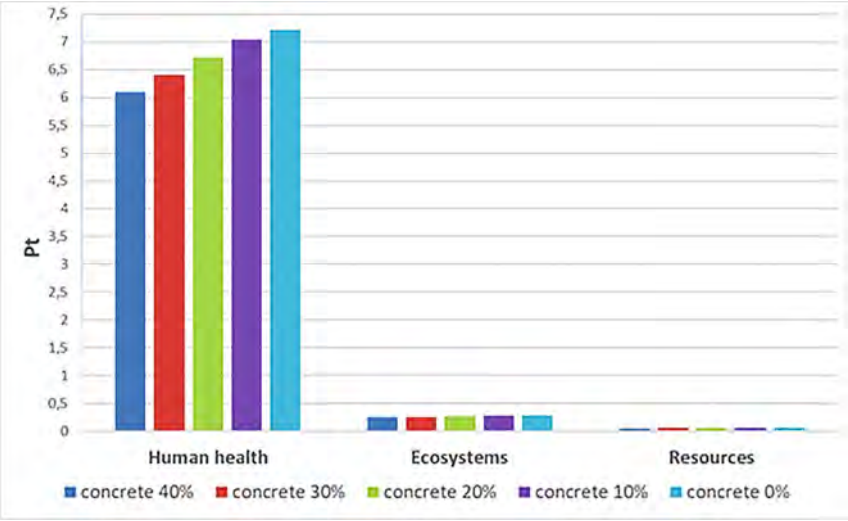


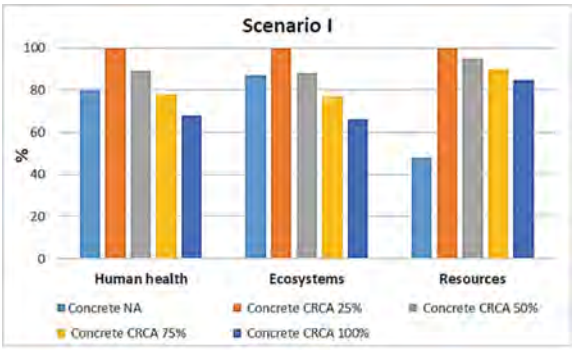
Fig. 1. Normalized damage categories for aggregate replacement by RCAs (S0, S1, S2, S3 and S4) in concrete production.

From Fig. 1 becomes clear that concrete with RCAs is more environmentally friendly than standard concrete, and as the percentage of RCAs is higher the lower is the impact. In addition, the figure demonstrates that the greatest impact for all the 5 scenarios is on human health, followed by the ecosystem quality and finally by resource scarcity. The results of this study are in accordance with literature such as the work of Alibeigibeni et al. [15] that highlights the positive environmental impacts of using RCAs, including the reduction of landfill waste, conservation of natural resources, and lowering of energy consumption, as well as the work of Fraj & Idir [16] in which the results showed that global warming indicator impact is greater for NAs compared to RCAs. Therefore, RCAs can be an attractive alternative to the natural ones in the production of concrete provided that the RCAs are not transported from far away and are of high grade, to avoid the need for large quantity of additional cement.

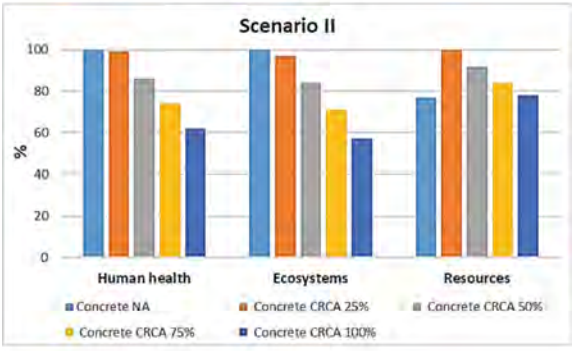
3.2 Use of Pre-carbonated RCAs in Concrete Production

Regarding the impact of the use of CRCA in concrete production, they are presented in Fig. 2. At 100% replacement rate of NAs with CRCA, the impacts on human health and ecosystem quality are reduced by up to half of the contribution of standard concrete for Scenario III (Fig. 2c), where the distance factor is ignored.

a)



b)



c)

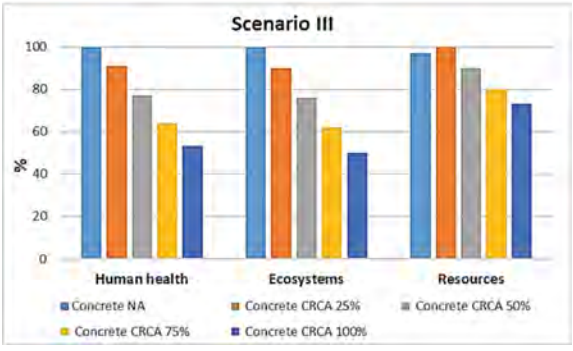


Fig. 2. Impact of a) Scenario I, b) Scenario II and c) Scenario III on human health, ecosystem quality and resource scarcity for the use of pre-carbonated RCAs in concrete production.

The results prove that the factor of transportation affects significantly the effectiveness of the use of CRCA in concrete production since in Scenario I no essential mitigation of the environmental impacts was observed compared to standard concrete and Scenario II and III. The results of the specific study agree with previous works [9, 14] which proved that accelerated carbonation is feasible at an industrial scale in concrete production, with results consistent with laboratory experiments, and with positive environmental impacts when waste transport is limited. In addition, the work of Zhang et al. [17] evaluated the net emission reduction and economic efficiency of using concrete debris in 14 global

regions via LCA and life cycle costing to fully consider the inputs and outputs in carbonation systems. It was reported that accelerated carbonization of RCAs can contribute to significant emission reductions, from 7.9 to 78.1 kg CO_2e per ton of RCA, offsetting approximately 45% of the emissions associated with concrete materials and 5.5% of the life cycle emissions of concrete structures. However, emission reductions were not observed in all regions due to differences in plant technology and variation of distances. It was observed that the reduction of the emissions depends largely on regional characteristics. Similarly, in the study of Pu et al. [1] the importance of transportation in mitigating environmental impacts is emphasized proving once again the importance of including waste transport in the evaluation of the environmental footprint.

4 Conclusions

In the present study, an LCA analysis was conducted to investigate the environmental impact of RCAs used in concrete production. The possibility of CRCA to be used, as well as the transportation distance was also examined.

The results proved that:

- RCAs from CDW contribute significantly to the reduction of the environmental impacts of the construction sector. By increasing the percentage of RCAs in concrete that replace the NAs the environmental impact of concrete decreases.
- CRCA not only improves the properties of RCAs (e.g. their workability, mechanical performance and durability) but also minimizes the environmental impacts, especially regarding human health and ecosystem quality.
- Waste transport is an important parameter for the effectiveness of the study, as the results prove to be better when the distances are lower or without taking them into account.

In conclusion, the main parameters affecting the efficiency of the method are the degree of aggregate replacement and the transportation distance, which require further investigation at an industrial level.

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Opportunities for the Valorization of Steel Furnace Slags (SFS) Waste in Romania Within the Circular Economy Framework

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Abstract. The transition from a linear economic model to a Circular Economy has become a strategic priority at both the global and European levels, driven by the need to reduce natural resource depletion. The principles of the Circular Economy highlight the continuous circulation of materials through reuse, recycling, and valorization, which transforms waste/by-products from environmental problems into beneficial secondary resources. Within this framework, the valorization of industrial waste streams represents a key opportunity for advancing circular practices in the construction and materials sectors. One particularly relevant category is steel furnace slag (SFS), a major by-product of the steelmaking industry. In Romania, significant quantities of SFS have accumulated in landfills, many of which remain largely unvalorized despite their considerable potential as secondary raw materials. These deposits not only occupy large land areas and pose environmental management challenges, but also represent a strategic resource that could reduce dependence on natural aggregates and support the development of more sustainable construction materials. In this study, talk about electric arc furnace (EAF) steel slag, a non-metallic material composed mainly of oxides, silicates, and other constituents that may pose environmental risks if disposed of improperly, as one of several types of steel furnace slag (SFS), a by-product of the steel manufacturing process, consisting of non-metallic oxides and silicates during the refining of molten steel. Consequently, the valorization of SFS waste has become a central theme in the context of circularity and sustainability. Exploring their potential applications, ranging from cement and concrete production to road infrastructure, can offer both environmental and economic benefits.

Keywords: EAF slag · Circular Economy · industrial waste valorization · natural aggregates · sustainable construction materials

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1 Introduction

1.1 The Transition from the Linear Model to the Circular Economy Model

The construction sector remains one of the most resource-intensive industries in Europe, consuming huge quantities of natural aggregates while generating significant waste streams throughout the life cycle of buildings. Similarly, the steel production sector has generated and continues to generate substantial volumes of industrial by-products and waste. Among these, steel slag accounts for a considerable share, accumulating over time and raising increasing environmental concerns, such as land use restrictions and long-term management of slag stockpiles. In particular, Steel Furnace Slags (SFS) waste, generated during basic oxygen furnace (BOF) and electric arc furnace (EAF) steelmaking processes, represents one of the most significant mineral by-products within the metallurgical industry [1, 2]. Stainless steel manufacturing processes contribute significantly to overall slag generation in Europe, with annual quantities estimated at 15–17 million tons across various production stages, including casting processes, EAF melting, AOD and VOD refining stages and ladle treatment [1, 3]. Like construction and demolition waste, these SFS wastes pose complex environmental challenges when they are not properly recovered or landfilled.

In the current context of European regulations, maintaining a linear economic model based on extraction, production, and disposal is no longer compatible with sustainability objectives. Recent EU policies increasingly promote the transition toward a circular economy, encouraging waste prevention, recovery of secondary resources, and reintegration of materials/waste into production cycles. The shift from the traditional linear model to circular value chains is schematically illustrated in Fig. 1 [4].



Fig. 1. Schematic representation of the transition from a linear to a circular economy model

An important step in this transition is Regulation (EU) 2024/1252 on critical raw materials, which aims to strengthen the European Union's strategic autonomy in raw

material supply. The regulation promotes the identification and recovery of critical materials from both primary and secondary sources, including industrial residues, and sets targets to be achieved by 2030 for increased domestic extraction, processing, and recycling capacities. In this context, historical slag deposits and steel production residues are increasingly regarded as potential secondary resource reservoirs supporting EU circular economy objectives [4, 5].

However, the transition from waste management to resource recovery cannot be based only on legislative factors. The effective integration of SFS waste into circular value chains needs a systematic assessment of their performance in terms of environmental impact throughout their life cycle, as well as their physical and mechanical behavior and durability under operating conditions.

1.2 Romanian Context

Steel production has historically played a significant role in Romania's industrial development, particularly in regions such as Galați, Hunedoara, and Călan, where integrated and Electric Arc Furnace steel (EAF) plants have operated for decades [2]. As a result of these activities, considerable quantities of metallurgical residues, including steel furnace slags (SFS), have been generated and accumulated over time in stockpiles associated with former or currently operating industrial platforms [2, 6].

Although part of these materials has been reused in construction-related applications, a substantial fraction remains insufficiently integrated into structured circular value chains, contributing to land occupation and long-term environmental management requirements [2, 6]. In addition to technical and economic constraints, the valorization of metallurgical residues in Romania has been influenced by fragmented regulatory practices and limited implementation mechanisms specifically tailored to secondary mineral resources [2].

In the context of the European Union's evolving regulatory framework regarding critical raw materials and circular economy objectives, these slag deposits increasingly constitute not only an environmental responsibility but also a potential strategic secondary resource reservoir [4]. However, their systematic quantification, characterization, and structured integration into sustainable construction systems remain at an early stage, highlighting the need for coordinated technical, environmental, and policy-aligned approaches at the national level [2].

2 Materials and Methods

2.1 Material Origin and Sources

The efficient utilization of steel furnace slag (SFS) is a process that begins with the identification and mapping of existing material stocks, both from current steel production and historical accumulations. Understanding the origin, quantity, and spatial distribution of these residues is a prerequisite for their integration into circular construction systems [1, 2]. In Romania, metallurgical residues, including SFS, are associated with former and active industrial platforms, forming significant accumulated deposits that remain only partially valorized [2, 6].

Specialized literature and national environmental reports provide quantitative assessments and partial inventories of metallurgical waste accumulations in Romania [2, 6]. However, the integration of these data into a unified and digitally structured resource mapping framework remains limited. In this regard, Industry 4.0 technologies have been identified as potential enablers for improving the traceability, monitoring, and strategic management of secondary material resources. In this context, applying Industry 4.0 principles to steel slag management could enable the systematic mapping, characterization, and performance-based allocation of SFS resources within circular value chains in construction [7, 8].

Table 1 summarizes the available data regarding metallurgical slag deposits in Romania, as reported in existing literature and national environmental documentation. This synthesis aims to present a consolidated overview of their scale, distribution, and documented characteristics.

Table 1. Data regarding metallurgical slag deposits in Romania

Source	Name	Description	Area (Ha)
Platon et al. [9]	Slag and ash storage facility CET I and II Islanița	This type of landfill is classified as containing non-hazardous waste.	290
	Slag and ash storage facility Turceni Thermal Power Plant	This type of landfill is classified as containing non-hazardous waste.	250
	Slag and ash storage facility Mintia Deva thermal power plant	This type of landfill is classified as containing non-hazardous waste.	101
	SIDEX S.A. Galaţi slag storage facility	This type of landfill is classified as containing hazardous waste.	90
	SIDERURGICA S.A. Hunedoara slag storage facility	This type of landfill is classified as containing hazardous waste.	80
Baera et al. [10, 11]	Țerova Steelworks Slag Dump (Reșița, Caraș-Severin County)	EAF slag derived from local industries from the Romanian Western Region.	–

2.2 Steel Furnace Slags: Material Description and Technical Characteristics

Steel furnace slags (SFS) are mineral by-products generated during steel refining in basic oxygen furnace (BOF) and electric arc furnace (EAF) processes. Their physicochemical characteristics depend on the steelmaking route, raw materials, and operational parameters involved in production [1]. In the Romanian industrial context, EAF-based steel production represents a significant technological pathway, making EAF slag particularly relevant for circular valorization strategies [2]. EAF slag is typically characterized by

a complex mineralogical composition dominated by calcium silicates, ferrites, wüstite, and other oxide phases formed during high-temperature reactions between fluxes, scrap metal, and impurities [1, 12]. These phases provide high density, abrasion resistance, and favorable mechanical performance, supporting the use of EAF slag as aggregate in concrete and road construction applications [1, 10, 11].

From a physico-mechanical perspective, steel slags generally exhibit high compressive strength and good resistance to mechanical wear, enabling their potential substitution for natural aggregates in construction materials [10, 13]. However, certain compositional aspects must be considered, particularly the presence of free calcium oxide (CaO) and free magnesium oxide (MgO), which may cause delayed volumetric expansion in the presence of moisture. Therefore, proper characterization of slag, including the assessment of expansion potential and leaching behavior, is required before large-scale implementation [11, 14]. Upon exposure to moisture, free CaO undergoes hydration according to "Eq. (1)".

$$CaO + H_2O \rightarrow Ca(OH)_2 \tag{1}$$

This reaction leads to volumetric expansion due to the higher molar volume of calcium hydroxide compared to calcium oxide, potentially generating internal stresses in confined systems [14, 15]. A similar mechanism may occur for MgO hydration, although at slower rates [15]. However, proper processing, aging, or treatment can mitigate these limitations and enable the controlled integration of SFS into construction materials [11, 14].

Chemically, SFS mainly consists of oxides such as CaO, SiO_2, FeO/Fe_2O_3, MgO, and Al_2O_3, forming complex crystalline and amorphous phases during cooling [1, 12]. Phases such as dicalcium silicate (C_2S) and tricalcium silicate (C_3S) may contribute to latent hydraulic behavior under certain conditions [12].

Controlled carbonation can further stabilize SFS by forming calcium carbonate through reactions between Ca-bearing phases and atmospheric CO_2, improving dimensional stability while enabling CO_2 sequestration [11, 14]. These transformations highlight the dual nature of SFS, where reactive components may cause instability if unmanaged but can also be utilized through engineered treatments to enhance environmental and structural performance. Therefore, a comprehensive characterization covering mineralogical composition, mechanical performance, and environmental behavior is essential for the responsible valorization of SFS within circular economy frameworks.

2.3 Valorization Opportunities of SFS in Construction

Steel furnace slags (SFS) have been investigated as secondary raw materials in various construction applications, offering multiple valorization pathways aligned with circular economy principles [1, 2].

Use as a Supplementary Cementitious Material

The high calcium content and the presence of silicate phases in steel slag create potential for partial replacement of cement or clinker in cementitious systems. However, its hydraulic reactivity is generally lower than that of traditional supplementary cementitious materials, and stabilization or pre-treatment may be required to control volumetric

instability [1, 12]. Research focusing on carbonation and mineral transformation has demonstrated that chemical modification of steel slag can improve its stability and environmental performance, enhancing its suitability for binder-related applications [11, 14].

Use as an Aggregate Substitute in Cementitious Composites

One of the most established valorization routes for SFS is its use as a partial or total replacement of natural aggregates in concrete or mortar. Due to its high density, angular particle shape, and mechanical resistance, SFS may enhance mechanical performance when properly processed [2, 10, 11]. Experimental investigations have shown that cementitious materials incorporating SFS as aggregate substitute can achieve compressive strength and durability comparable to reference compositions, provided that expansion risks associated with free CaO and MgO are controlled [10–12, 14].

Case Study: Investigation on the Use of SFS Waste as Aggregate Substitute in Cement-Based Materials

Within the research program conducted by NIRD URBAN-INCERC, PN 23 35 04 01 of the Nucleu Programme of the National Research Development and Innovation Plan 2022–2027 "ECODIGICONS", supported by the Ministry of Research, Innovation and Digitalization, ongoing investigations focus on the valorization of SFS waste originating from the Reșița steelmaking platform (Caraș-Severin County, Western Romania) as a secondary aggregate in cement-based materials. The study evaluates the feasibility of substituting natural aggregates with EAF in different proportions (10–50%) in order to assess the potential of this industrial by-product for construction applications [10, 11]. Preliminary observations indicate that SFS can be effectively incorporated into the cementitious matrix, showing good compatibility and favorable interfacial interaction due to its angular particle morphology. Although the investigations are still at an early stage, the initial results indicate promising prospects for the use of SFS as a partial substitute for natural aggregates in cement-based materials.

Road Infrastructure Applications

The mechanical robustness and abrasion resistance of SFS make it particularly suitable for road engineering applications, including base and sub-base layers. Large-scale utilization in road construction enables bulk consumption of SFS materials, contributing significantly to natural aggregate conservation [1, 13]. The angularity and surface texture of slag particles can improve interlocking behavior in granular systems, supporting structural stability in pavement structures [13].

Carbonation and Environmental Valorization

Beyond structural applications, accelerated carbonation of steel slag has emerged as an additional valorization strategy. Carbonation promotes the conversion of reactive Ca-bearing phases into stable carbonate compounds, reducing leaching potential while simultaneously enabling CO_2 sequestration [12, 14]. This approach integrates environmental mitigation with material stabilization, reinforcing the role of SFS within circular construction frameworks.

3 Conclusions

The transition from a linear to a circular economic model in the construction sector requires not only legislative alignment but also structured technical implementation. In this context, the digitalization of industrial by-product/waste flows, supported by Industry 4.0 principles, could significantly improve the traceability, mapping, and strategic management of steel furnace slag (SFS) resources at the national level [4]. A digitally integrated inventory framework would enable a clearer overview of existing stockpiles and facilitate their targeted integration into construction value chains.

The findings of this study highlight that SFS represent a technically viable and environmentally relevant secondary resource. When properly characterized in terms of mineralogical composition, physico-mechanical performance, and environmental behavior, SFS can be safely and efficiently valorized in multiple construction applications. The challenges associated with volumetric stability or chemical reactivity do not represent inherent limitations, but rather parameters that must be controlled through adequate processing, stabilization, and performance assessment.

SFS demonstrates significant potential for the substitution of natural aggregates, partial replacement in cementitious systems, and large-scale application in road infrastructure. Beyond structural applications, carbonation-based treatments further enhance their environmental profile, contributing to emission reduction and material stabilization [12, 14].

Therefore, the responsible integration of SFS into construction systems should not be regarded as a waste management alternative, but as a strategic component of resource efficiency and circular economy implementation. With proper characterization, technological control, and coordinated policy support, SFS can transition from an environmental liability to a valuable secondary raw material within sustainable construction practices.

Acknowledgements. This work was carried out within the Nucleu Programme of the National Research Development and Innovation Plan 2022–2027, supported by MCID, "ECODIGICONS" project no. PN 23 35 04 01: "Fundamental-applied research into the sustainable development of construction products (materials, elements, and structures, as well as methods and technologies) that utilizes current national resources to enhance the eco-innovative and durable aspects of Romania's civil and transport infrastructure", financed by the Romanian Government.

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Evaluation of Biofilm Formation on Oil-Impregnated and Outdoor Exposed Wood in the Eastern Black Sea Region of Turkey

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Abstract. In this study, biofilm formation was investigated on Scots pine (*Pinus sylvestris*) and Eastern spruce (*Picea orientalis*) wood samples impregnated with various vegetable oils such as sunflower oil, waste sunflower oil, raw linseed oil and soybean oil. Wood samples were impregnated with the oils in two stages. Wood samples impregnated with oils were exposed to outdoor weather conditions for a 9-month period. Some macroscopic examinations with the naked eye were carried out on wood surfaces where a biofilm layer formed. Several biofilm characterization tests were conducted on samples. The physical properties (equilibrium moisture content and compression strength) and the surface characterization properties (color changes, glossiness) of wood specimens were determined. The results show that a noticeable biofilm layer has formed on some wood specimens.

Keywords: Biofilm · wood protection · oil impregnation · weathering · fungi

1 Introduction

The "ecological approach" is becoming increasingly important in wood preservation and surface treatments. The biofilm wood protection surface treatment is one of the latest innovations in wood coating field. Biofilms are communities of microorganisms structured within a protective extracellular polymeric substance (EPS) matrix, attached to living or non-living surfaces. Although bacteria are more prominent in terms of biofilm formation, it is known that some fungal species also form biofilm layers similar to bacteria. It has been reported that fungal species such as *Candida*, *Aspergillus*, *Trichosporon*, and *Aureobasidium* in particular have the potential to form biofilms [1, 2]. It is stated that the diversity of biofilm-forming fungi varies depending on the geographical conditions exposed; therefore, larger datasets and studies conducted in different locations are needed to reach clearer conclusions regarding the product [2]. The aim of this study is to evaluate whether there is a potential for natural biofilm formation in the Eastern Black Sea Region of Turkey.

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2 Material and Method

2.1 Wood Material and Impregnation with Oils

In the experiments, samples obtained from Scots pine (*Pinus sylvestris*) and Eastern spruce (*Picea orientalis*) lumber, dimensioned to 150 × 75 × 20 mm (longitudinal × tangential × radial), were used. A total of 12 test samples and 4 control samples were prepared, with 4 samples for each variation. Prior to testing, all specimens were conditioned in a climate chamber until they attained a moisture content of 12%. The test samples were impregnated with various vegetable oils such as sunflower oil, waste sunflower oil, raw linseed oil and soybean oil. Oil treatment of the test samples was carried out in two stages; first keeping in a hot oil bath at 160 °C for 30 min; and then in a cold oil bath at 20 °C for 30 min. The vacuum created by the temperature difference facilitated the penetration of the oil into the wood. Weight percent gain (WPC) and oil retention values were calculated as described by Yıldız et al. [3].

Test specimens impregnated with oils and non-impregnated control specimens were exposed to outdoor weather conditions for a period of 9 months starting from June 2025, using the test setup shown in Fig. 1. Physical tests and surface characterization tests were performed on the samples taken from this test setup at the end of the 3rd and 9th months.

2.2 Physical Tests

In order to determine whether the samples exposed to the outdoor environment had suffered any loss of resistance, the compressive strength parallel to the grain was determined according to TS ISO 13061-17 [4]. For the compressive strength test, the samples were dimensioned to 2 × 2 × 3 cm (tangential × radial × longitudinal direction), and the equilibrium moisture content was also determined on the same samples.



Fig. 1. Appearance of Scots pine and spruce wood natural biofilm specimens, impregnated with four different oils and exposed in the field, at the beginning of July (2025).

2.3 Surface Characterization Tests

Color measurements were determined using the CIELab color system. Color measurements were taken from three different points on the longitudinal surface of the wood

samples. The total color change (ΔE) in the samples was determined by comparison with the initial color measurement. Gloss measurements of the test and control samples were performed at 85° angle using a gloss meter (PCE-GM 100). The measurements were obtained as the arithmetic mean of 10 measurements for each surface, taken parallel to the wood fibers.

3 Results and Discussion

Oil Retention. The average weight percent gain (WPG), thickness swelling (TS) and retention values are given in Table 1.

Table 1. Values obtained from oil impregnation.

Species	Oil	Retention (kg/m^3)		WPG (%)		TS (%)	
		160 °C	200 °C	160 °C	200 °C	160 °C	200 °C
Scots Pine	Soybean	220	298	44	62	−0.16	−0.28
	Sunflower	247	328	50	72	0.82	0.31
	Waste Sunflower	439	290	86	63	−3.42	0.40
	Raw Linseed	255	–	45	–	0.32	–
Eastern Spruce	Soybean	92	127	22	33	0.64	0.62
	Sunflower	81	77	19	19	0.29	0.34
	Waste Sunflower	143	76	30	16	−2.90	1.81
	Raw Linseed	64	–	15	–	0.76	–

In spruce wood, the increase in temperature only led to an increase in the retention amount of specimens impregnated with soybean oil, whereas decreases in retention amounts were recorded with the rise of temperature to 200 °C for sunflower oil and waste sunflower oil impregnations. There are other studies indicating that high-temperature applications cause a reduction in oil uptake [5–8]. The effectiveness of vegetable oil treatments can vary depending on the properties of the oil, the amount of oil absorbed, its leaching from the wood, the temperature and duration of the impregnation method, the wood species, and the sample dimensions [9–11].

3.1 Physical Tests

Table 2 shows the equilibrium moisture content (EMC) values, and the compressive strength (CS) values parallel to the grain. According to the table, a decrease in DRM values was detected relative to the control in Scots pine except for those impregnated with sunflower oil. However, in the spruce it was recorded that the DRM values in the test specimens increased compared to the control. It is reported that tall oil treatments reduced

the water uptake of pine sapwood [12]. Wang and Cooper reported that they obtained reduction in water absorption and water uptake values, and 40% anti-swelling efficiency (ASE) in spruce wood specimens impregnated with soybean oil, palm oil, and wax [9, 13]. It can be stated that the impregnation process with oils provides mechanical stability in the long term. In the literature, the average compressive strength value of untreated spruce and Scots pine wood has been reported as approximately 28–30.5 N/mm^2 and 49.70 N/mm^2, respectively [14, 15].

Table 2. Compressive strength and EMC values of the samples.

Species	Oil	Compressive strength (N/mm^2)				EMC (%)			
		160 °C		200 °C		160 °C		200 °C	
		3M*	9M**	3M	9M	3M	9M	3M	9M
Scots Pine	Soybean	45	67	67	–	11.4	11.7	11.9	–
	Sunflower	48	52	61	–	13.7	14.1	14.3	–
	Waste Sunflower	47	77	69	–	10.7	10.9	10.8	–
	Linseed	36	74	–	–	8.2	8.6	–	–
	Control	42	79	42		12.5	13.2	12.5	–
Spruce	Soybean	37	59	56	–	8.7	9.4	9.2	–
	Sunflower	31	56	55	–	8.3	9.0	8.9	–
	Waste Sunflower	43	64	64	–	8.4	8.9	8.7	–
	Linseed	37	57	–	–	11.3	11.7	–	–
	Control	30	50	30	–	7.3	8.0	7.3	–

* Indicates the values at the end of the 3rd month;
**Indicates the values at the end of the 9th month

3.2 Surface Characterization Tests

Macroscopic Observation. The natural weathering test on wood samples impregnated with oils was carried out in the coastal region of Trabzon, Turkey (40°81′85′′N, 39°79′10″ E). The macroscopic observations were made with the naked eye on the wood surfaces where a biofilm layer had formed. The factors considered here are macroscopic observation elements such as whether the biofilm is of homogeneous density and thickness, and whether it covers the wood surface in a way that completely conceals the wood tissue (annual rings or wood fibers). Accordingly, as seen in Fig. 1, no biofilm formation was observed on the specimens of either wood species during the first 3 months of outdoor exposure testing. In contrast, as can be seen in close detail in Fig. 2, the development of a dark-colored biofilm layer on the test specimens of both wood species was found to be quite remarkable at the end of approximately 9 months. Fig. 3 shows the initial and 9th-month images of specimens.



Fig. 2. Image of Scots pine and spruce wood natural biofilm test specimens in January 2026.

According to the images in Fig. 3; the surface morphology of the untreated natural Scots pine control specimen exhibits characteristic textural features specific to the species (top left). Compared to the control specimen, it is observed that sunflower oil exhibits a homogeneous distribution on the surface and forms a thin, protective layer over the wood fibers (top right). In contrast, when examining the 9-month pine test specimens, the smooth and light-colored fibrous structure of the control specimen has been completely replaced by a dark-colored (gray-black), matte, and heterogeneous natural biofilm layer. It is observed that the surface is entirely covered by melanin pigments and bio-polymeric matrix produced by microorganisms (likely mold/staining fungi). This biofilm layer has largely concealed the characteristic anatomical details of the wood fibers, imparting a holistic yet textured appearance to the surface (bottom left). On the other hand, in the spruce test specimen, compared to the control specimen, the surface has lost its characteristic light color, transforming into a 'silvery gray' appearance with occasional black spots. It is observed that the surface is covered by a heterogeneous natural biofilm layer formed by microorganisms (especially mold fungi) (bottom right). It has been reported in the relevant literature that similar biofilm formations have been observed [16, 17].

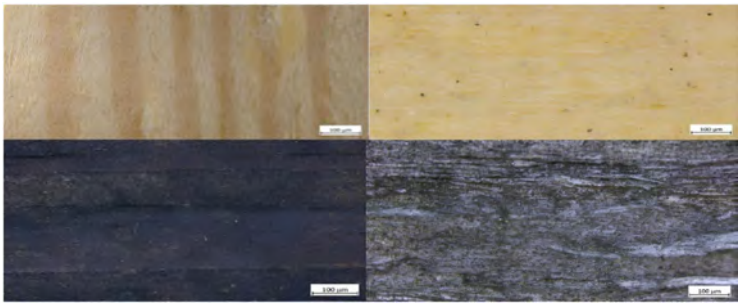


Fig. 3. Top left: Scots pine non-impregnated control specimen, Top right: Scots pine specimen impregnated with sunflower oil, Bottom left: 9-month natural biofilm Scots pine test specimen, Bottom right: 9-month natural biofilm Eastern spruce test specimen.

Surface Color and Gloss Evaluation. The 3-month and 9-month color change (ΔE) of Scots pine and spruce wood test and control specimens are shown in Fig. 4. As seen in Fig. 4, the (ΔE) values in the 9th-month data at 160 °C decreased significantly compared

to the 3rd month. Over time, the oils may have begun to absorb the destructive effects of UV rays and moisture in the outdoor environment by forming a natural biofilm layer on the wood surface. While color change increased over time in the control groups (from approximately 28 to 57), it decreased in the oil-treated specimens. Accordingly, it can be stated that oil impregnation protects the wood against photo-degradation (sunlight-induced graying) and stabilizes the color over time. In the general trend, it was observed that spruce wood was slightly more prone to color change compared to Scots pine. This situation can be explained by the anatomical structure of spruce wood and its oil absorption capacity being different from that of Scots pine. There are studies reporting that color change on biofilm-covered surfaces is much less compared to control specimens [16–18].

The 3rd-month and 9th-month average gloss values parallel-to-grain of the test and control group specimens are shown in Fig. 5. According to the figure; while 3-month specimens at 200 °C exhibited high gloss even in the control group, a general decrease is observed in 9-month specimens at 160 °C. This indicates that high temperature renders the surface more 'glassy' due to hemicellulose degradation on the wood surface, but over time, outdoor conditions (biofilm) mask this effect. Scots pine, thanks to its wide heartwood and resin canals, provided a more suitable ground for oil penetration, which ensured that its gloss values remained higher compared to spruce. In a study, it was reported that gloss significantly decreased on surfaces where biofilm formed compared to the control [16].

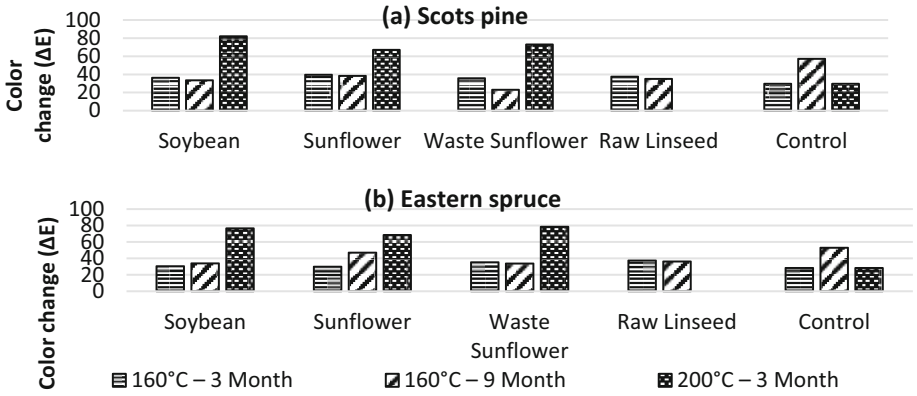


Fig. 4. Color change (ΔE) values of (a) Scots pine and (b) Eastern spruce samples treated with different natural oils under various thermal treatment conditions after weathering exposure.

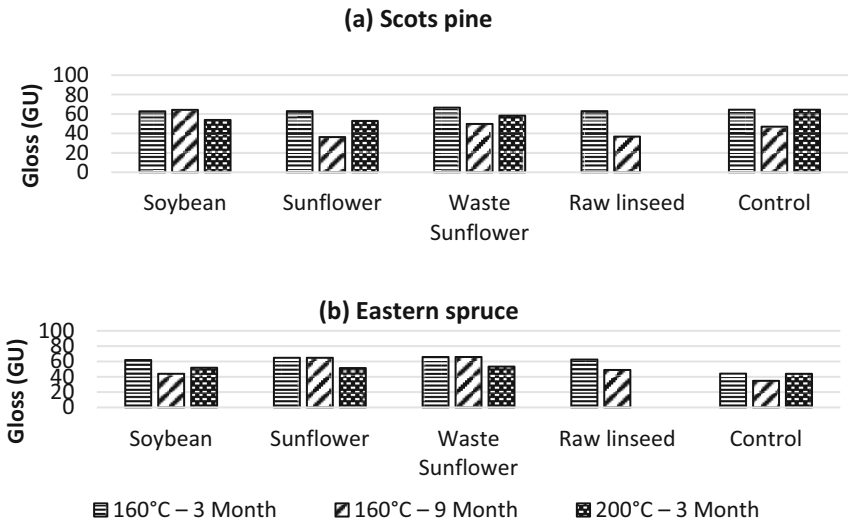


Fig. 5. Gloss (GU) values of (a) Scots pine and (b) Eastern spruce samples treated with different natural oils under various thermal treatment conditions after weathering exposure.

4 Conclusions

The 9-month results obtained in the study indicate that there is significant potential in terms of biofilm-forming microorganisms on wood surfaces in the Eastern Black Sea Region of Turkey. However, it will be possible to reach more detailed data with the 15-month results of the outdoor exposure test. Furthermore, with the definitive identification of the dominant species through DNA analyses, new research topics can be introduced based solely on these species.

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Material Reuse in the Building Sector: Insights from Municipal and Industry Actors in Sweden

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Abstract. The building sector is a major contributor to global CO_2 emissions, resource consumption, and construction and demolition waste. A large share of these impacts is linked to the production of new materials and the linear take–make–dispose logic that still dominates building processes. Increasing material reuse is therefore essential for reducing embodied carbon and extending the life of construction resources toward climate neutral cities. This study investigates current practices, barriers, and opportunities for building-material reuse across municipalities, construction companies, consultants, and reuse operators in Sweden, using a mixed-method approach combining quantitative surveys and qualitative interviews. The results show that material reuse practices vary widely across the sector. Several operators report rapidly increasing interest, with demand for reused materials rising by over 50% in the past 2 years. Respondents estimate that more than 75% of the materials they collect can be reused with no or minimal processing, and contamination levels are generally low. Despite this potential, actors describe reuse processes as significantly slower, sometimes 25–50% longer than conventional practices. Municipal involvement remains modest, while digital tools and platforms such as Palats and CCBuild are emerging as important enablers for identifying and managing reusable materials. Despite existing challenges, most participants expect reuse to become standard practice within the next decade. The study concludes that cross-sector collaboration, targeted support mechanisms, and improved regulatory clarity are essential to mainstream reuse practices. Strengthening logistics, documentation, and collaboration across municipalities, industry, and innovators can foster a more circular and resource-efficient construction ecosystem in Sweden.

Keywords: Building material reuse · Circular renovation · Construction industry · Construction and demolition waste · Material bank · Viable cities

1 Introduction

The construction sector plays a central role in modern societies by providing essential infrastructure while also being associated with significant environmental impacts. The building sector accounts for around 40% of global energy consumption, 30% of energy-related carbon emissions, and a large share of raw material use, while construction and demolition waste (CDW) represents more than 35% of total waste generation in the

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European Union [1–3]. Much of this impact results from the continued reliance on a linear "take–make–dispose" model in building processes.

Circular economy (CE) approaches aim to reduce these impacts by extending material lifecycles through reuse, recycling, and recovery, thereby lowering embodied carbon emissions and reducing demand for virgin resources [4, 5]. Among these strategies, building material reuse is particularly promising because it preserves the value of construction components while avoiding emissions associated with new material production.

At the European level, construction material reuse is influenced by regulatory frameworks such as the Construction Products Regulation (CPR), the Ecodesign for Sustainable Products Regulation (ESPR), and waste directives. In Sweden, these frameworks are implemented through national regulations including the Planning and Building Act (PBL), the Building Regulations (BBR), and the Environmental Code [6–8].

Despite increasing policy attention, material reuse remains limited in practice due to barriers such as regulatory ambiguity, lack of standardized documentation, logistical constraints, fragmented supply chains, and limited coordination between demolition and construction processes [9–13].

Sweden provides a relevant context for studying material reuse as the country aims to achieve a fossil-free built environment by 2045. However, national assessments indicate that reuse practices remain limited and reuse marketplaces are still developing [14].

This study investigates current practices, barriers, and opportunities for building material reuse within the Swedish construction ecosystem using a mixed-method approach combining qualitative interviews and quantitative surveys with municipalities, housing companies, construction firms, and reuse operators.

The study addresses the following research question:

RQ: How are building material reuse practices implemented across different stakeholder groups in the Swedish construction sector, and what barriers and enabling factors influence their wider adoption?

This study contributes to the literature in three ways. First, it provides empirical insights into reuse practices across multiple stakeholder groups within the Swedish construction ecosystem. Second, it identifies key operational barriers and enabling factors influencing the implementation of reuse practices. Third, it highlights the mismatch between the high technical reuse potential of construction materials and the relatively low level of reuse adoption in construction projects [4, 9, 10, 12].

2 Methodology

This study employs a mixed-method approach combining qualitative interviews and quantitative surveys to examine material reuse practices across the construction ecosystem. Data collection consisted of 11 semi-structured interviews followed by a structured online survey administered to each participant. Interviews were conducted with stakeholders across the circular construction value chain, including municipalities, housing companies, reuse operators, and construction firms. The participants represented a diverse range of actors within the Swedish construction ecosystem. Participants were selected using purposive sampling to ensure representation across key stakeholder groups involved in material reuse practices. The study aimed to capture perspectives from

actors occupying different positions within the circular construction value chain rather than achieving statistical representativeness. Given the relatively small sample size, the findings should be interpreted as exploratory and indicative of broader sectoral patterns rather than fully generalizable across the Swedish construction sector. Following each interview, participants received a survey link to provide quantitative input on reuse frequency, estimated material volumes, processing time, and perceived barriers. Interview topics addressed organizational roles, material reuse practices, collaboration patterns, operational challenges, economic considerations, and policy influences. All interviews were recorded, transcribed, and anonymized where requested. Likert-scale questions assessed the relative importance of economic, environmental, and regulatory factors, while open-ended questions allowed respondents to describe specific practices and challenges.

Qualitative and quantitative data were analyzed using complementary approaches and integrated during interpretation. Interview data were used to identify recurring themes, while survey responses enabled cross-actor comparisons and identification of broader patterns. Research quality was strengthened through methodological triangulation and the inclusion of diverse stakeholder groups across the construction value chain. Participation was voluntary and informed consent was obtained from all respondents, while individual responses remain anonymous.

3 Results and Discussion

3.1 Stakeholder Roles in the Circular Construction Ecosystem

The empirical findings reveal a circular construction ecosystem characterized by clearly differentiated but interdependent stakeholder roles (Fig. 1).



Fig. 1. Roles, responsibilities and flows in material reuse.

Municipalities primarily act as enablers and coordinators by providing policy guidance, climate strategies, and platforms for collaboration. Housing companies play a

central operational role by integrating material reuse into renovation and construction projects, managing internal depots, and applying digital inventory systems. Reuse providers function as hubs for collection, sorting, refurbishment, and resale of materials while also serving as knowledge centres. Construction companies are responsible for dismantling activities, technical verification, and on-site integration of reused materials, whereas renovation projects represent the stage where circular ambitions are translated into concrete design and construction decisions.

These findings indicate that circular construction in Sweden is emerging but remains unevenly implemented across stakeholder groups. While circular economy approaches encompass a wide range of practices, including recycling, eco-design, and industrial symbiosis [4, 15], the practical implementation of material reuse in construction remains fragmented. This reflects broader transition challenges frequently discussed within socio-technical transition and circular economy research, where institutional structures, market conditions, and actor coordination influence the adoption of circular practices [4, 10, 12].

3.2 Extent of Material Reuse Across Stakeholder Groups

Survey results show substantial variation in material reuse across stakeholder groups (Fig. 2). Housing companies report substantially higher reuse rates than construction firms, while reuse operators indicate that a large share of collected materials can be reused with minimal processing.



Fig. 2. Material reuse adoption rates by stakeholder group (survey results).

Municipalities and municipal housing companies report typical reuse levels of approximately 10–30% of total material volumes in many projects, suggesting that circular construction is feasible in practice when supported by long-term organizational commitment and sustainability strategies [14, 16]. In contrast, private construction companies often operate within project-based structures characterized by tighter time constraints and financial margins, which may limit the adoption of reuse practices. Similar barriers have been identified in previous studies, including fragmented supply chains, regulatory uncertainty, and misaligned stakeholder incentives [10, 17].

3.3 Reused Material Types and Processing Characteristics

Table 1 summarizes the reuse frequency and technical suitability of different material categories. Structural materials such as brick, stone, and metal show the highest reuse potential, while insulation, roofing materials, and technical systems are reused less frequently due to performance and certification constraints.

Table 1. Material reusability and frequency matrix.

Material	Reuse potential
Doors & windows	Very high (95%)
Brick	Very high (90%)
Metal (Steel)	Very high (88%)
Stone	Very high (85%)
Glass	High (82%)
Wood	High (80%)
Roofing materials	Low (35%)
Insulation	Very low (30%)
Technical systems	Very low (25%)

Processing times also vary depending on organizational context. Centralized reuse hubs typically process materials within one to 3 days, while on-site reuse processes often require more than 7 days due to scheduling constraints, coordination challenges between demolition and construction phases, and limited storage capacity (Table 2).

Table 2. Material processing times: operational comparison.

Centralized reuse hubs	On-site construction
1–3 days processing	$>$ 7 days processing
Dedicated infrastructure	Scheduling constraints
Specialized staff	Coordination challenges
Streamlined sorting	Limited storage

These results highlight the importance of infrastructure and logistics in enabling reuse practices. Dedicated reuse facilities and structured workflows enable faster sorting, refurbishment, and redistribution of reclaimed materials. Previous research similarly emphasizes the role of reverse logistics systems in improving material recovery and reuse within construction supply chains [3, 18].

3.4 Digital Material Management Practices

Digital material tracking differs significantly across organizations. Based on survey responses, housing companies and reuse operators report substantially higher levels of digital tracking (over 75%) using platforms such as CCBuild and Palats, whereas construction firms report considerably lower levels of adoption (under 25%).

Limited digital integration reduces transparency and traceability of reusable materials, which constrains the ability to match supply and demand across projects. Digital platforms therefore represent an important enabling factor for scaling circular construction practices [19].

3.5 Barriers, Collaboration, and Enabling Factors

Across stakeholders, the most frequently reported barriers to material reuse include lack of time, insufficient expertise, logistical constraints, limited access to reused materials, and regulatory uncertainty (Fig. 3).

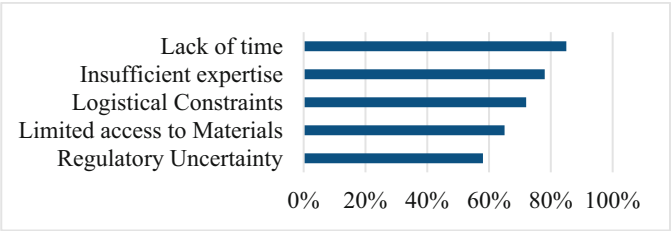


Fig. 3. Barriers to material reuse implementation (survey results).

Collaboration also emerges as a key factor influencing reuse outcomes. Although the sample size limits statistical interpretation, respondents reporting stronger collaboration with reuse operators and suppliers also report higher reuse levels, suggesting a potential relationship between collaboration intensity and reuse outcomes. However, collaboration remains limited by fragmented procurement structures, competition between firms, and mismatched project timelines.

These findings highlight a mismatch between the technical reuse potential of construction materials and their practical implementation. While reuse operators estimate that more than 75% of collected materials could be reused with minimal processing, construction companies report reuse in only a small share of projects. This suggests that the primary barriers are not technical feasibility but organizational, logistical, and institutional constraints [9, 12].

3.6 Economic and Environmental Implications

Economic impacts of reuse are perceived as highly context dependent. Reuse may increase labour and logistics costs, although potential benefits include avoided disposal

fees, reduced procurement of new materials, and reputational value associated with sustainability goals. Municipal climate funds and EU funding mechanisms also support pilot projects and reduce financial risks.

Environmental benefits are primarily associated with avoided carbon emissions from new material production, although systematic use of life-cycle assessment (LCA) tools remains limited. Scaling circular construction requires coordinated action across the construction ecosystem, including improved digital infrastructure, strengthened logistics systems, enhanced collaboration mechanisms, and clearer regulatory frameworks.

4 Conclusion

This study examined how building material reuse is implemented across different stakeholder groups within the Swedish construction ecosystem and identified key barriers and enabling factors influencing its wider adoption. The results show that circular construction is emerging but remains unevenly implemented across the sector. Municipalities and municipal housing companies demonstrate higher levels of reuse adoption than private construction firms, suggesting that organizational commitment and long-term sustainability strategies play an important role in enabling reuse practices.

The findings also reveal a gap between the technical reuse potential of construction materials and their practical implementation in construction projects. While reuse operators report substantial reuse potential, organizational, logistical, and regulatory constraints continue to limit wider adoption.

Scaling circular construction therefore requires coordinated action across the construction ecosystem. Strengthening digital material tracking, improving logistics systems, enhancing collaboration between stakeholders, and clarifying regulatory frameworks will be essential to support wider implementation of material reuse and advance the transition toward a more circular built environment. The findings contribute to ongoing discussions on circular construction transitions by highlighting the gap between technical reuse potential and practical implementation within the construction sector.

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Multicriteria Analysis of Additives in Earthen Construction

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Abstract. Construction materials are typically evaluated primarily based on their performance and costs rather than sustainability, which places pressure on low-carbon materials such as earth to be technologically enhanced to remain competitive. Consequently, sustainable earthen materials are increasingly modified with additives to meet contemporary construction requirements by improving mechanical, durability, and thermal properties. Yet the diversity of additive types and the wide distribution of existing studies hinder a systematic overview of current knowledge.

To address this issue, a three-stage analytical model was developed consisting of Data Collection, Data Mining, and Data Visualization. A comprehensive literature database on additives in earthen construction was assembled using digital research tools. Subsequently, a semi-automated workflow based on AI-assisted language models was used to extract and classify key information from publication metadata of 241 selected papers. The extracted data were organized into four analytical categories: additive type, property addressed, origin, and reported influence.

By translating these classified relationships into a network-based visualization, the approach enables a clearer contextualisation of findings across a fragmented research landscape. This refined representation supports the identification of associations, thematic clusters, and emerging research directions that are often overlooked in conventional reviews. The visualization thereby turns the heterogeneity and scale of the dataset into an analytical advantage, enhancing the foundation for systematic, data-driven research and future standardisation in modified earthen materials.

The results further reveal a strong research focus on strength-related properties, while durability, hygrothermal behaviour, and environmental performance remain comparatively underexplored.

Keywords: Additives · Earthen materials · Data mining · Data visualization · Network visualization

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1 Introduction

Earth has long been recognized as a circular-low-carbon construction material that, in principle, can exhibit structural behaviour comparable with concrete. However, in its raw or untreated form, earthen material generally does not achieve the mechanical performance required for contemporary structural applications [1]. To improve the materials properties, additives such as natural fibers, chemical binders, or industrial by-products are widely used [2], with their application varying depending on geographical conditions, resource availability, and industrial context.

However, the existing literature related with the influence of the additives in these material properties, is highly heterogeneous and fragmented, with additive effects typically evaluated only for individual properties [3], while quantitative assessments of their overall influence remain limited. In practice, many additives simultaneously affect multiple characteristics [1], such as mechanical properties, durability, rheology, or thermal, making direct comparison between studies difficult.

Given the multiplicity of variables, including additive types, origins, properties and their interrelations, a structured methodological framework is required to organize, analyses, and interpret the dispersed information. Data mining techniques, aim to identify valid, potentially useful, and understandable correlations and patterns within large datasets [4], making them a strategic tool for exploring literature on additives in earthen materials and analysing their property relations. Data mining represents one essential step in a multi-stage workflow designed to derive meaningful insights from heterogeneous data sources.

Therefore, the objective of this study is to systematically analyse additive-property relations in earthen construction additives literature using AI-assisted data-mining and network analysis.

2 Methodology: Data-Driven Analytical Framework

A common Data-mining workflow consists of data preprocessing, pattern discovery, and pattern interpretation [4]. Accordingly, this research is structured into: data collection, AI-assisted data mining, and network mapping methodology.

2.1 Data Collection

This stage involved compiling a collection of scientific literature on additives used in earthen construction. For this purpose, the literature discovery platform Litmaps [5] was selected due to its ability to explore citation networks and expand literature collections through AI-assisted recommendations and ranking algorithms.

Initially, 15 papers were manually selected using the search query, based on the search "Earthen Construction Additives" [6–20], where Litmaps propose the most connected publications (based on the number of references and citations in other researches).

Between 10th November and 26th November 2025, the collection was expanded to a total of 277 publications trough AI-assisted recommendations out of the 15 seed papers, based on the citation connectivity and shared keyword patterns. The search process

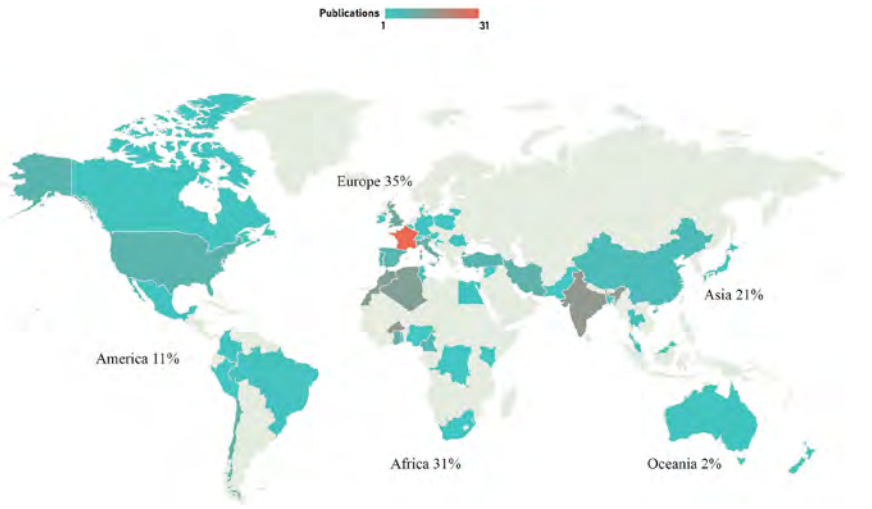


Fig. 1. Global heat map illustrates the geographic distribution and relative concentration of publications by country of origin.

was stopped when newly suggested papers were no longer directly related to additives, ensuring a consistent dataset.

Of all selected publications, 241 were accessible in full-text (PDF) through institutional access (HBC library subscriptions) and were included in the final dataset, where 46.9% of them ($n = 113$) were published between 2020 and 2025. A further 42.3% ($n = 90$) date from 2010–2019, while 10.8% ($n = 26$) were published before 2000 until 2009. The geographic distribution of the publications spans multiple countries, as shown in Fig. 1.

2.2 AI-Assisted Data Mining

The finalised data-set was exported from Litmaps in BibTex format and organized through a reference manager to facilitate attaching the full text. These PDF documents were processed using GROBID [21], a machine-learning-based system for parsing scholarly documents. All texts were extracted as structured TEI-XML files, enabling efficient conversion into a tabular dataset for further processing in Excel. The resulting workflow followed the sequence: PDF, GROBID, TEI-XML, Excel.

After organizing the data in Excel, the AI interaction was defined. Instead of training a custom language model, which would require extensive datasets and training time, the Open AI API [22] was used to perform the text analysis. A controlled instruction set as prompt was developed, to extract just explicit additive-property relationships, avoiding duplicates and including brief evidence descriptions of their selection.

Further processing the 241 collected papers, 1861 additive–property interactions were identified under non-standardized terminology. To ensure clearer classification, a predefined list of property categories was established: Acoustic, Deformation, Density, Durability, Economical, Environmental, Geotechnical, Hygrothermal, Rheology,

Stiffness, Strength, and Thermal. An additional Generic category was introduced to temporarily store interactions that could not be directly classified, avoiding forced assignments.

Subsequently, a second AI-assisted classification step was implemented, to reassign the extracted properties to predefined categories. The prompt assigns exactly one category per interaction, allowing synonym and partial matches while prioritizing the main property. After this step, Generic represented 13% of the interactions. Manual review reassigned 29 cases, reducing unclassified interactions to 11%.

2.3 Network Mapping and Analysis

Network mapping and analysis were performed using Gephi [23], an open-source platform for network visualization and exploration. In the model, nodes represent additives and material properties, while edges indicate relationships between them. Edge weights (lines thickness) correspond to the frequency of additive-property interactions. Also a modularity analysis was performed using the Louvain Method [24], allowing to identify clusters based on their connection patterns.

Visual attributes were applied to facilitate interpretation. Node size reflects the degree of connectivity, colors represent modularity classes, highlighting clusters of related additives and properties. The network geometry was generated using force-directed layout algorithms, which spatially arrange nodes according to the strength of their relationships.

3 Results

The additive–property network map (Fig. 2) consists of 505 nodes and 1670 edges, representing relationships between additives and material properties extracted from the data-set. Of the nodes, 491 correspond to additives and 12 to property categories.

The average node degree is 2.01, meaning that each additive is, on average, linked to two properties. This indicates that most additives are associated to a limited number of properties, resulting in clearly identifiable clusters. The average path length is approximately 1, Indicating that nodes are connected through very short relational paths, strongly influence for tight connections with other nodes.

Community detection using the Louvain modularity algorithm identified six clusters (modularity = 0.40). Clusters sizes are uneven, with the largest cluster comprising 35.31% of the network, followed by clusters containing 16.01%, 15.1%, 9.7% and 9.5% of the nodes. The smallest cluster represents 4.2%. Strength and stiffness form the most connected region of the network, as shown in Fig. 3 and belong to the same cluster, whereas other properties such as durability, hygrothermal behaviour, deformation, and density show lower connectivity.

Several additives exhibit higher connectivity within the network, including lime, cement, fibers, polypropylene fibers, and rice husk, indicating their frequent association with multiple material properties in the analysed literature. Strength-related properties account for the largest share of additive-property interactions (32%), followed by thermal (12%), durability (11%), and deformation (11%) properties, while acoustic, environmental, and economic properties occur less frequently.

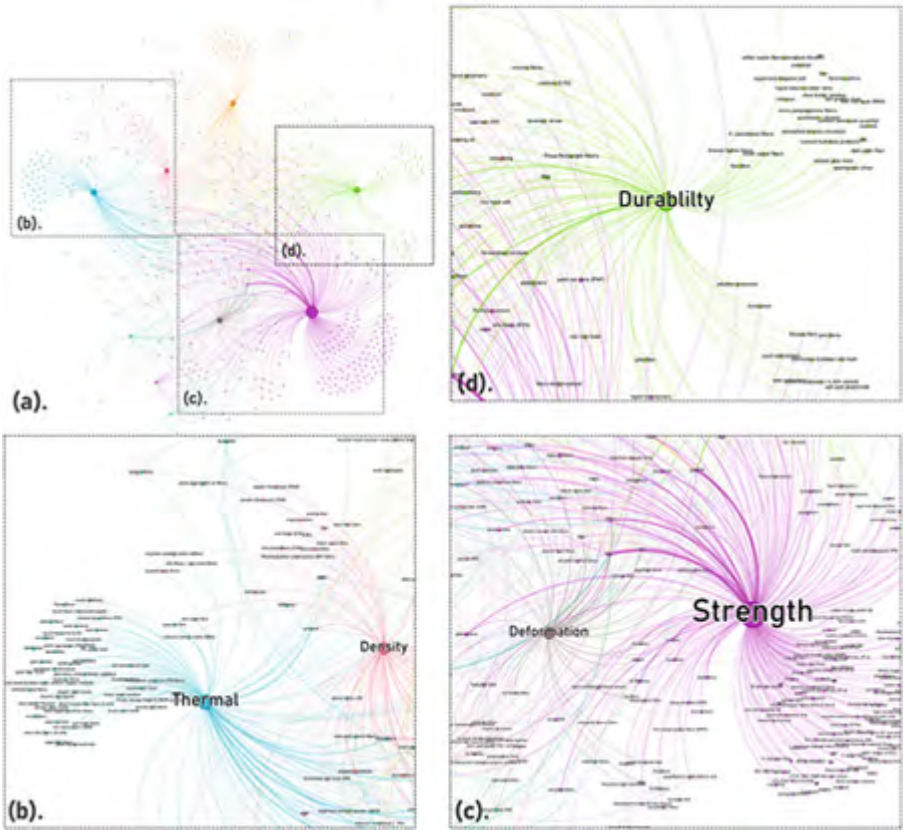


Fig. 2. Network visualization of additive–property relationships: (a) complete network graph; (b) Thermal-related cluster; (c) Strength-related cluster; and (d) Durability-related cluster.

From a structural perspective, the network reveals several subclusters and localised structures. Some additives appear near the center of the network due to their connections with multiple properties, indicating materials that influence several performance aspects simultaneously. In contrast, smaller and weakly connected clusters highlight areas where research remains limited.

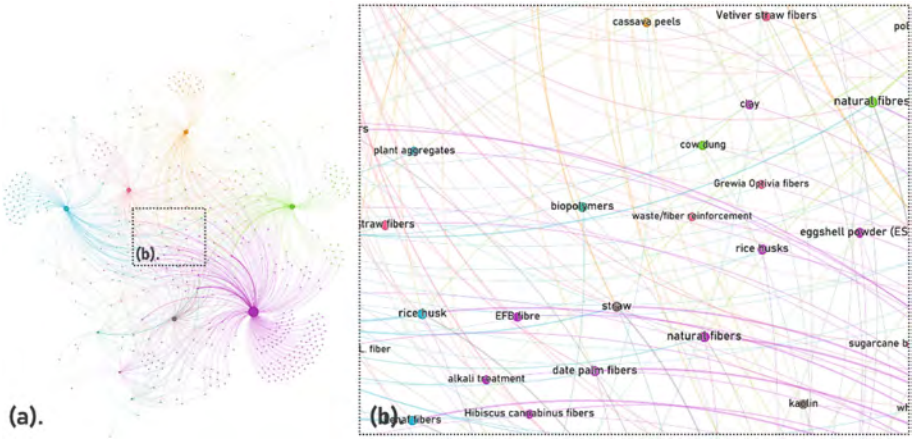


Fig. 3. Network visualization of additive–property relationships: (a) complete network graph; (b) Additives located in the center of the plot, mainly natural fibers-related.

4 Discussion

The additive–property network reveals a strong concentration of research on strength-related properties. This emphasis reflects the widespread use of strength as the primary indicator for assessing the structural applicability of earthen materials. Consequently, many additives are mainly investigated for their influence on mechanical performance. Other relevant aspects, such as durability or thermal behaviour, appear less frequently, suggesting that current research prioritises structural performance rather than multidimensional optimization of earthen materials.

The network structure further shows that highly connected additives are predominantly natural fibres. In contrast, conventional stabilisers such as cement or lime, are frequently associated primarily with mechanical performance. This pattern suggests that natural additives are commonly investigated from a more multidimensional perspective, involving several material properties simultaneously. Consequently, single-property evaluation approaches may underestimate the overall contribution of natural additives to earthen-material systems. Future research would therefore benefit from broader, multidimensional assessment frameworks that enable more robust comparison and evaluation of additives.

It is important to consider in these outputs, certain deviation concerning the absolute interpretation of the literature topics' tendences. The current study was developed on 15 seed papers; however, it is expected that using a larger or different set of initial publications could lead to different outcomes.

Methodologically, the dataset reflects the characteristics of the collected literature, including its temporal distribution and predominance of English-language publications. Furthermore, although AI-assisted classification enables the analysis of larges datasets, variation in terminology interpretation may introduce uncertainties. This highlights the need for controlled vocabularies and iterative validation procedures when applying automated classification approaches.

5 Conclusion

This study demonstrates that data-driven approaches can provide a structured overview of the fragmented literature on additives in earthen construction. By combining literature mining, AI-assisted data extraction, and network analysis, patterns within 241 scientific publications were identified and visualised. The resulting additive-property network reveals a strong research focus on strength-related properties, confirming that mechanical performance remains the dominant criterion in the evaluation of earthen materials. In contrast, durability, hygrothermal behaviour, and environmental performance appear considerably less represented, highlighting important research gaps. Methodologically, the results illustrate the potential of AI-assisted literature analysis for synthesising large and heterogeneous datasets and for identifying dominant research directions and underexplored areas in the field.

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From Waste to Resource: Sustainable Cement Solutions for a Low-Carbon Future

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Abstract. Regarding new policies for the achievement of zero CO_2 emission cement production by 2025 and 2050 in the EU, the cement industry is investigating new processes of cement clinker production that can lead to emission reduction and achieve adequate properties of produced cement. One of the main paths for the reduction of CO_2 is by leading the process at lower temperatures, which means lower emissions by fuel combustion, and integration of alternative raw materials. Alternatives of raw materials are industrial by-products like red mud, waste material of Bayer process of alumina and aluminium production, which is harmful to the environment because of high alkalinity and inadequate storage of produced waste. In this research aim was the development and characterization of new cement materials based on red mud waste (50 and 80 mass % added), to confirm the possibilities of its use as a potential alternative for naturally exploited raw materials. Also, to lower the production temperature, systems were successfully thermally treated at a maximum temperature of 1200 °C, which is 200–300 °C lower than the temperature of thermal treatment of cement clinker in industrial plants. Final products underwent chemical-mineralogical characterization (XRF, FTIR analysis), which confirmed adequate composition for cement material. After cement production and characterization, testing of hydrated cement (mechanical testing and SEM analysis) was performed. As a result, it is shown that adequate chemical composition and mechanical properties were obtained with the use of 50 and 80 mass % of red mud for cement clinker production, which can confirm possibilities for the successful introduction of red mud as a raw material in the cement production industry.

Keywords: environment · reduction of CO_2 · cement clinker production · waste materials · red mud

1 Introduction

The rapid growth of the construction sector strongly influences how materials are developed, selected, and used. To support construction and building industry, production of building materials optimization of various production processes is in the main focus of nowadays research. Cement is one of the key materials required in the construction

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industry. However, its production involves the consumption of large quantities of raw materials, which may lead to the long-term depletion of natural resources. One of the approaches to reducing this impact is the utilization of waste materials with similar chemical compositions, which can serve as alternative raw materials in cement production and contribute to more sustainable resource management [1, 2].

One of well-known and extensively investigated waste material for production of different cementitious materials and Portland cement replacement is red mud (RM). Red mud is a waste material of Bayer process for alumina production, which has hazardous impact, due to its high alkalinity (pH around 12–13) and presence of various radionuclides. Its large production that is estimated to 1.5 tons for 1 ton of alumina, is problematic for its disposal, but can be beneficial for production of different materials where raw materials can be replaced with such waste. Previous studies have shown that, utilization of RM to obtain Portland cement and special aluminate cements is possible from mixing ordinary raw materials with different amount of RM [1, 3–5].

Main reason for RM utilization in production of Portland and special cement raw materials mixture is its chemical composition. High amounts of alumina, silica and iron-oxide can enhance formation of main cement clinker mineral phases, such as alite and belite (C_3S, C_2S), tricalcium-aluminate (C_3A) and tetracalcium-alumoferrite (C_4AF). Mineral phases C_3A and C_4AF and calcium-sulfoaluminate can be present in produced special aluminate and sulfoaluminate cements. Possibility to utilize from RM in this case is due to similar composition to bauxite, which is originally used for production of special aluminate cement. Successful preparation of special cements using RM, is important task that has impact on optimization of production processes with ecological impact, sustainability enhancement and lowering CO_2 production [3–7].

In this study, main aim was to optimize production process of special cement using RM (50% and 80%) as main raw material that is mixed with synthetic belite precursor and synthesized belite to get insight in possibility of implementing such mixture to obtain cement with enhanced mechanical properties after hydration process. Also, lower thermal treatment temperature was tested (T_{max} 800 °C and 1200 °C) to contribute in domain of energy consumption reduction.

2 Materials and Methods

2.1 Materials

In this study, eight systems were prepared mixing RM with two different components, Table 1. First component is synthetic belite precursor (thermally non-treated) and second is produced synthetic belite obtained from this mixture. Preparation of precursor was done by homogenization method. Calcium-hydroxide (17.78 g) was mixed with 150 mL of distilled water. After few minutes 250 mL of distilled water is added. Mixture is homogenized on magnetic stirrer for 15 min (800 rpm), without heating. After 15 min, microsilica (7.21 g) is added to mixture and homogenization continued for 30 min. Obtained mixture is dried in oven on 105 °C until solid. To produce synthetic belite, dried mixture is grinded in planetary mill (30 min, 250 rpm), and thermally treated (heating rate 10 °C/h; T_{max} 800 °C; standing time 90 min; rapid cooling for 10 min until 500 °C; 12 h cooling until reaching room temperature).

After synthetic belite and precursor synthesis, mixtures with RM were prepared, and each system is thermally treated in 2 regimes: heating rate 10 °C/h; T_{max} 800 °C; standing time 90 min; rapid cooling for 10 min until 500 °C; 12 h cooling until reaching room temp.; heating rate 10 °C/h; T_{max} 1200 °C; standing time 90 min; rapid cooling for 10 min until 900 °C; 12 h cooling until reaching room temp.

Table 1. Composition of prepared systems

System	Red mud (%)	Synthetic belite precursor Bo (%)	Synthetic belite Bp (%)	T_{max} (°C)	Final product label
$S_{M50Bo50}$	50	50	/	800	CEM_1
$S_{M80Bo20}$	80	20	/	800	CEM_2
$S_{M50Bp50}$	50	/	50	800	CEM_3
$S_{M80Bp20}$	80	/	20	800	CEM_4
$S_{M50Bo50}$	50	50	/	1200	CEM_5
$S_{M80Bo20}$	80	20	/	1200	CEM_6
$S_{M50Bp50}$	50	/	50	1200	CEM_7
$S_{M80Bp20}$	80	/	20	1200	CEM_8

2.2 Methods

Obtained final products ($CEM_{1–8}$) were tested to obtain results for chemical-mineralogical composition, microstructural and mechanical properties before and after cement hydration. XRD analysis was performed on *Bruker D4 Endeavour* instrument. Microstructure characterization was performed by SEM analysis on instrument *JEOL JSM 6460 LV.* Mechanical properties were tested according to aluminate cement testing standard EN 14647:2014 after 6 h, 24 h and 14 days of hydration, with modification of standard testing (according to standard 160 × 40 × 40 mm molds should be used, but in this study 40 × 10 × 10 mm molds were used).

3 Results

3.1 XRD Analysis-Cement Powder

Synthesized cements were analyzed (all except CEM_7) and mineral forms comparison was performed according to peaks intensities and T_{max}, Table 2.

Table 2. Comparison of mineral forms content in synthesized cements (+++ high content; ++ medium content; + low content; – not identified)

Final product	System	T_{max} (°C)	C_3A [8]	Belite [8]	Grosite [9]	Anorthite [10]	Krotite [9]	Mayenite [9]	Hematite [10]
CEM_0	Com. cement	–	++	–	++	–	+++	++	–
CEM_1	$S_{M50Bo50}$	800	+++	+	++	+	–	–	–
CEM_2	$S_{M80Bo20}$	800	+++	+	++	+	–	–	–
CEM_3	$S_{M50Bp50}$	800	+	+++	+	+++	–	–	–
CEM_4	$S_{M80Bp20}$	800	++	+++	+	+++	–	–	–
CEM_5	$S_{M50Bo50}$	1200	++	+++	++	+	+++	+++	–
CEM_6	$S_{M80Bo20}$	1200	+++	+++	++	+++	+	+++	++
CEM_8	$S_{M80Bp20}$	1200	+++	+++	++	+++	+	+++	++

According to results showed in Table 2, all systems treated on T_{max} 800 °C contain (C_3A), belite, grosite and anorthite phases in different amount. Systems with synthesized belite have higher content of belite and anorthite phases, and systems with belite precursor have higher content of C_3A and grosite, which means that for production of aluminate cement favorable composition is with belite precursor. According to C_3A (tricalcium-aluminate), CA_2 (grosite), C_2S (larnite - belite) presence on such low temperatures indicates production possibility of hydraulic aluminate cement on way lower temperatures than standard temperatures for aluminate cement.

In case of cements treated on T_{max} 1200 °C there are some differences. Belite quantity is not dependent on precursor or synthesized belite usage. Beside same mineral forms as in $CEM_{1–4}$ systems, presence of krotite, mayenite and hematite (except CEM_5) is identified. Krotite presence is crucial for aluminate cements, because of promoting early cement hydration. Also, according to phase diagram, identified minerals are formed on approx. 1300 °C. As maximal temperature of thermal treatment was 1200 °C, successful synthesis of such cement at lower temperature can have significant impact on energy efficiency in aluminate cement production (1350–1450 °C) [4]. Comparing with commercial aluminate cement, it is shown that similar contents of aluminate cement mineral phases are in a commercial and synthesized cements.

According to all shown results, different raw materials composition and thermal treatment temperatures can have significant impact on obtaining cements with various composition of cement clinker minerals.

3.2 Mechanical Testing-Hydrated Cements

After 14 days of hydration, compressive and flexural strength were measured and compared to commercial aluminate cement prisms mechanical strength values. For each system, three samples were tested and mean value was calculated (prism dimensions 40 × 10 × 10 mm). Comparing results of all systems, it was concluded that CEM_4 and CEM_5 have highest value for mechanical properties, Table 3. CEM_4 has higher value

of compressive strength than CEM_5, and similar compression strength as commercial aluminate cements. CEM_5 has compressive strength similar to belite cements, even if its chemical composition is between aluminate and belite cement. Optimization of obtained systems could improve overall mechanical strength-

Table 3. Mechanical testing mean values after 14 days

Final product	Mean val. flexural strength (MPa)	SD	Mean val. compression strength (MPa)	SD
Comm. Aluminate cement	6.07	0.10	9.20	0.12
CEM_4	0.98	0.08	7.10	0.10
CEM_5	0.90	0.07	2.70	0.14

3.3 SEM Analysis

SEM analysis was performed to obtain information about hydration mineral forms presence and their structure. To confirm similar morphology to aluminate cement, commercial aluminate cement sample was prepared and cured for 14 days and also examined. Figure 1 shows SEM micrographs for different samples with marked mineral forms.

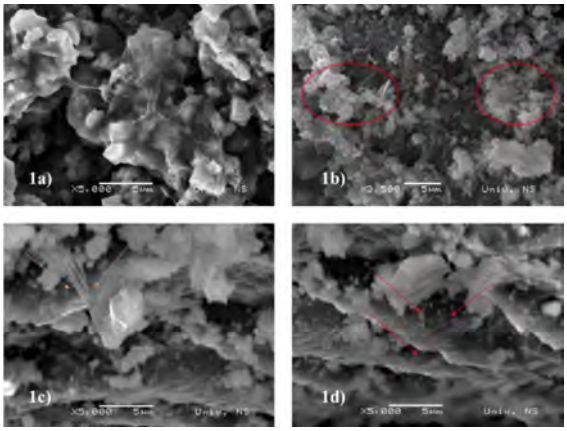


Fig. 1. SEM micrographs of samples after 14 days of hydration: a) commercial aluminate cement x5000; b) CEM_4 x3500; c) CEM_5 x5000; d) CEM_5 x5000

Figure 1b show hydrated CEM_4 samples with presence of C-S-H and C-A-H phases (details on Fig. 1b) which is consequence of belite and other cement clinker minerals hydration [11]. Comparison of morphologies for aluminate cement (Fig. 1a) and CEM_4 shows great similarity of samples. Figure 1c shows CEM_5 with marked xonotlite needle-like hydration product (Fig. 1c orange arrow markings). On Fig. 1d, red arrows point to C_2AH_8 presence, which is confirmed to be typical hydration product for aluminate

cement. According to obtained results, possibility of hydration products formation for synthesized cements for both systems CEM_4 and CEM_5, is confirmed.

4 Discussion

To verify correlation with other publications, in Table 4 there are summarized results for produced cements, CEM_4 and CEM_5 and summarized results of different publications where RM is used for Portland cement production. Difference that should be highlighted is that according to our investigation, synthetic belite and its precursor were not used in any existing publications for production of such aluminate cements with RM.

Table 4. Summary results of obtained results and similar research articles

Publication/system	RM (mas. %)	T_{max} (°C)	Mineral forms	Compression strength (MPa)	Water:cement ratio	Sample dimensions (mm)
CEM 4	80	800	C_3A,C_2S, CAS_2,CA_2	7.1 [14 days]	0.5	40 × 10 × 10
CEM 5	50	1200	C_3A, C_2S, CAS_2, CA, CA_2, $C_{12}A_7$	2.7 [14 days]	0.5	40 × 10 × 10
Singh et al. [4]	15% addition in clinker prod.	1350	C_4A_3S,C_4AF, CT, C_2AS	9.8 [28 days]	0.4	n.i.*
Tsakiridis et al. [12]	3.5% addition in clinker prod.	1450	C_2S, C_3S, C_3A, C_4AF, CaO_{free},MgO	45 [28 days]	0.5	160 × 40 × 40
Nguyen, Do [6]	33%	1180	α-C_2S, C_3A, C_4AF	29.3 [28 days] (without sand)	0.21	n.i.*

n.i.* no information

Results from the table show maximal temperatures of thermal treatment 1450 °C, 1350 °C and the lowest of 1180 °C in the study by Nguyen and Do [6]. The study by Tsakiridis et al. [12] was conducted at a temperature of 1450 °C using a small amount of RM (only 3.5%). The RM based cement in these works achieved mechanical strength from 45 and 29.3 MPa. Singh et al. [3, 4] used 15% of RM with 47.5% limestone, 7.5% gypsum to produce cement with a sintering temperature of 1350 °C. The compressive strength of this cement was 9.8 MPa. The CEM_4 sample, which has 80% RM in its composition, has a compressive strength of 7.1 MPa after 14 days, which is close to the value obtained by Singh et al. [3, 4], but after 28 days. It is also important to note that the heat treatment of the CEM_4 sample was 800 °C, which is lower than the temperature

used by Singh et al. [3, 4]. To obtain further information and to confirm large-scale production, existing results should be further investigated and compared to some other analysis methods. CEM_5 has lower value for mechanical strength than any of shown results, so preparation of such cement should be more optimized.

5 Conclusion

According to obtained results, it can be concluded that utilization of RM in special cementation is possible by optimization of composition and other raw materials. In this work, cement production was based on synthetic belite and its precursor with RM. Eight systems were synthesized and preliminary analyzed after which two systems ($S_{M80Bp20}$-CEM_4; T_{max} 800 °C and $S_{M50Bo50}$-CEM_5, T_{max} 1200 °C) were chosen to be examined further. Results for mineral composition show similarities of these two systems to aluminate/belite cements.

Compared to the available literature data presented in this paper, the CEM_4 sample, which has 80% RM in its composition, has a compressive strength of 7.1 MPa after 14 days, which is similar to the values obtained by other researchers, but after 28 days. It should be noticed that thermal treatment temperatures were lower in cement production as for standard aluminate cements (800 °C for CEM_4 and 1200 °C for CEM_5), which means that with effective hydration of obtained cements synthesized on lower temperatures, possibility of sustainable and lower cost production can be achieved.

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Mechanical Performance of Soils Stabilized with Geopolymers Produced from Waste Generated by Brazilian Steel and Thermoelectric Industries

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Abstract. The limited availability of soil deposits and the demand for materials in road infrastructure have intensified the search for sustainable alternatives to improve soils used in pavement sublayers. Traditionally, chemical stabilization is carried out using Portland cement or lime, which, although effective, lead to environmental impacts due to natural resource consumption and greenhouse gas emissions. In this context, geopolymers emerge as solutions, as they are produced through the alkaline activation of industrial residues rich in aluminosilicates and exhibit cementitious behavior capable of modifying soils. This study presents the synthesis of geopolymers produced with waste from thermoelectric and steel industries for application in pavement sublayers. Geopolymers formulated with fly ash, steel slag, and coke dust were developed to assess their feasibility as stabilizers for soil mixtures. The precursor materials were treated, alkali-activated, and applied to a clayey soil, followed by mechanical testing, with emphasis on unconfined compressive strength (UCS) as a performance indicator. Stabilization was performed using 3% additive content, and specimens cured under moist and dry conditions for 7, 14, 21, and 28 days. Although early strength gains under moist curing modest, mechanical development increased over time, while air curing resulted in higher UCS values. The formulation containing coke dust exhibited performance, highlighting the potential of geopolymers to enhance soil properties in pavement applications. Overall, geopolymerbased stabilization represents an environmentally advantageous and feasible alternative for pavement construction, reducing dependence on conventional binders and supporting the reuse of industrial residues, promoting a circular economy.

Keywords: Alkaline Activation · Pavement Construction · Fly Ash · Steel Slag · Petroleum Coke Powder · circular economy

1 Contextualization

The industrial chain, in all its processes, results in the generation of waste. These residues are a consequence of every stage of production, whether in direct manufacturing activities or in secondary services such as maintenance, cleaning, construction works, and

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other operational processes. Such by-products, when not properly managed, lead to serious environmental consequences [1]. The management of the large volume of waste generated is one of the main challenges faced by the global population in the 21st century [2]. This situation imposes on companies the challenge of seeking technically and economically feasible disposal solutions, with the primary objective of minimizing environmental impacts [3].

With constant technological and demographic development, it is impossible to think about the construction industry without mentioning the environmental impacts generated, which directly affect present and future generations. This makes it necessary to adopt a vision of progress aligned with sustainability concepts and technological advances capable of reabsorbing waste, as well as an awareness of the finite nature of natural resources [4].

Road construction projects can be particularly highlighted, as they require considerable volumes of natural materials, which must ultimately achieve sufficient strength to withstand traffic loads [5]. This performance cannot always be achieved with the soils available in deposits located near the highways to be constructed. The use of fine soils or soils with low bearing capacity in pavement sublayers requires the application of stabilization techniques to improve their strength and geotechnical properties, with chemical stabilization being one of the techniques traditionally employed [6].

However, the environmental impacts resulting from the production of Portland cement and lime, which are the binders most used in this type of stabilization, raise concerns regarding their use. The production of these materials not only consumes large volumes of natural resources but also emits greenhouse gases in proportions estimated at 1 ton of CO_2 for each ton of cement produced. In this context, the construction industry has increasingly sought to adopt sustainable and economically viable techniques to ensure its continued development while preserving the environment and promoting the recycling of different types of waste in projects located near their production sites [7–9]. Geopolymers, therefore, become an environmentally less aggressive alternative to traditional binders, since through their synthesis it is possible to recycle various types of industrial waste that would otherwise be discarded and transform them into cementitious materials, if they are rich in aluminosilicates [10]. After alkaline activation, the waste materials can be applied in various forms, such as interlocking blocks, cementitious pastes, geopolymer concrete, soil stabilization, among others. This enables their use in all pavement layers.

For geopolymer synthesis to occur, the activation of precursors in an alkaline medium is required. These precursors must contain silicate (SiO_3) and alumina (Al_2O_3) in their chemical composition. Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) are the most used activators in such syntheses, as well as their combinations or, less frequently, potassium-based activators [11]. The alkaline activation process occurs in three stages. Initially, the alumina and silica present in the precursors are dissolved by the alkaline activator. In the second stage, the formation of an aluminosilicate gel begins, which reorganizes until equilibrium is reached. The third stage consists of polycondensation, at which point the geopolymer solidifies, exhibiting an amorphous and semicrystalline structure. The solidification process may occur instantaneously or take several days, depending on the mixture composition and the curing conditions adopted [12].

Given this scenario, the study of the application of local waste materials to produce alternative binders to Portland cement and lime is considered important and relevant. In this context, the present study aims to use fly ash, steel slag, and coke dust as geopolymer precursors applied to the chemical stabilization of a clayey soil, through mechanical and microstructural tests in which the improvements in the soil's mechanical properties resulting from geopolymer-based chemical stabilization were evaluated. In addition, the study seeks to contribute to the reduction of the carbon footprint associated with the use of conventional materials in chemical stabilization processes.

2 Materials and Methods

To achieve the objectives of the study, an experimental program was developed and divided into two stages. In the first stage, the activities focused on the basic classification of the studied soil, named Mombaça Soil (MS), which was classified according to the methodology defined by AASHTO (American Association of State Highway and Transportation Officials), using the results of grain size analysis [13], liquid limit [14], and plasticity limit [15] tests. In addition, MS was subjected to compaction tests [16], California Bearing Ratio (CBR) tests [17] and unconfined compressive strength tests to obtain parameters regarding its bearing capacity.

Fly ash (F), obtained from a coal-fired thermoelectric power plant, BSSF-type slag (Baosteel Slag Short Flow), designated as (B), and coke dust (C), both derived from the steelmaking industry, were used as geopolymer precursors. Still in the first stage, the precursors underwent prior treatment to remove salts present in the samples that could interfere with the quality of the synthesized product. After treatment, the precursors were activated with a 10 M sodium hydroxide (NaOH) alkaline solution and sodium aluminate ($NaAlO_2$). The treatment and synthesis process is described in [18]. Six geopolymers were synthesized with F as the primary base material, incorporating variations of 25%, 50%, and 75% of B or C.

The second stage of the experimental program corresponds to the application of the synthesized geopolymers, which were ground and sieved to pass through a 0.075 mm mesh sieve. The dry powder was applied to the soil as a stabilizing agent at a content of 3% by mass, to obtain the soil–geopolymer mixtures. The samples were compacted using intermediate compaction energy in a miniature apparatus [19], producing specimens 50 mm in diameter and 50 mm in height, with a maximum variation of 1 mm. After molding, the specimens were subjected to curing periods of 7, 14, 21, and 28 days. The curing conditions were defined as moist curing (MC) and dry curing (DC). Under MC, to prevent sudden moisture loss, the specimens were wrapped in plastic film to maintain moisture throughout the established period. Under DC, the specimens remained in direct contact with atmospheric air during the entire curing period.

After curing for the periods established in the experimental program, the specimens were tested to failure in a hydraulic press, at a displacement rate of 10 mm/min, to monitor the gains in unconfined compressive strength of the stabilized soil over time. In addition, with adaptations to standard [20], shrinkage and swelling tests were performed on the samples.

3 Results and Discussion

3.1 Geotechnical Characterization

After performing the basic geotechnical characterization through the conventional tests described in the experimental program, the data presented in Table 1 were obtained. It can be observed that SM was classified as a clayey soil of class A-6 according to the AASHTO classification methodology. The soil exhibits a high content of fines, with approximately 49.76% of the particles passing through the 0.150 mm sieve. The high fine fraction directly influences the material's consistency limits, which showed a liquid limit of 29% and a plasticity index of 16%, due to the significant presence of silt and clay particles.

Table 1. Geotechnical Characterization.

Soil	AASHTO	MDD (g/cm^3)	LL (%)	PL (%)	PI (%)	OMC (%)	CBR (%)	Exp. (%)	Shri. (%)	UCSM (MPa)	UCSD (MPa)
SM	A-6	2.46	29	16	13	10.1	3.0	0.30	0.47	0.45	2.69

The high fines content gives the soil undesirable properties for materials used in pavement construction, as it tends to be highly susceptible to slight moisture variations and to exhibit high deformability. An indicator of this behavior is the CBR value of only 3% obtained for the sample, as well as the UCS-M of 0.45 MPa, expansion of 0.30%, and shrinkage of 0.47%. Based on these results, it can be concluded that the soil, in its natural condition, would not be suitable for use in pavement sublayers.

3.2 Microstructural Characterization

The materials used as precursors, the natural soil, and the synthesized geopolymers were subjected to microstructural tests to achieve a better understanding of the synthesis processes. Initially, the materials were analyzed by X-ray fluorescence (XRF), which allows elemental identification, as presented in Table 2. The XRF analysis indicates the presence of silicon and aluminum oxides in the composition of fly ash, coke dust, and BSSF, highlighting the potential of these materials for geopolymer synthesis.

The synthesized geopolymers exhibit a composition similar to that of the precursors, in which the elements identified at the highest concentrations were iron (Fe), silicon (Si), aluminum (Al), and calcium (Ca). Geopolymers containing C show the highest Fe content in their composition, whereas samples incorporating steel slag increase the calcium content in the geopolymers that use it as a precursor. This may indicate the possible presence of carbonated materials.

3.3 Mechanical Tests

The expansion and shrinkage results measured 24 h after specimen molding are presented in Fig. 1a, b, respectively. In Fig. 1a, a decreasing trend in expansion can be observed

Table 2. Elemental composition of the samples (%).

Sample	Si	Fe	Al	Ca	K	P	Ti	S
SM	52.11	18.13	17.78	5.08	3.00	0.00	2.37	0.00
F	42.18	24.02	12.28	8.03	4.90	2.42	2.18	0.87
B	5.09	44.02	1.00	40.09	0.03	1.68	0.51	0.00
C	13.24	51.25	7.62	12.25	2.56	1.99	1.73	7.88
75F25B	18.31	46.47	5.04	20.70	2.57	1.14	1.89	0.32
50F50B	9.06	50.84	3.09	28.59	1.47	1.09	0.97	0.00
25F75B	16.49	49.33	4.78	20.54	2.76	1.16	1.70	0.00
75F25C	24.77	47.20	4.99	10.09	4.95	1.27	2.82	0.89
50F50C	18.77	52.86	6.52	10.23	4.07	1.31	2.94	1.09
25F75C	12.51	60.37	5.27	10.59	3.62	1.56	2.59	2.28

with the application of geopolymers to the soil, except for geopolymers 25F75B and 75F25C, in which expansion remained stable. All samples exhibited values below 0.5%, the recommended limit for pavement base layers. In Fig. 1b, it can be observed that, unlike expansion, which was more effectively controlled, shrinkage increased for all stabilized mixtures. Excessive shrinkage may lead to problems such as cracking, soil disintegration, and water infiltration into lower layers, and should therefore be carefully controlled [21]. indicate that the acceptable shrinkage range for tropical soils used in base layers should be between 0.1% and 0.5% to ensure satisfactory performance.

The addition of fly ash in stabilization processes leads to reductions in the maximum dry density (MDD) of the mixture due to its extremely fine particle size and lower density [22]. In addition, the greater specific surface area of the added fine particles requires a higher water content, which explains the increased shrinkage values. Shrinkage can be controlled in the field through proper management of material drying, by protecting stabilized layers with vegetation cover, plastic sheets, or by applying a bituminous prime coat.

The results of the unconfined compressive strength (UCS) tests for the stabilized samples are presented in Fig. 2a, b. The stabilized mixtures were subjected to moist curing (MC) and dry curing (DC) for periods of 7, 14, 21, and 28 days. A minimum 7-day strength value for lime-stabilized soil bases was adopted as a reference, according to [23], who uses the parameters defined by the Illinois Highway Department, requiring a minimum value of 1.034 MPa for base layers. This choice is justified by the better interaction of lime with fine and clayey soils when compared to Portland cement.

It can be observed that, at 7 days of curing, most samples had already exceeded the minimum required strength of 1.034 MPa for lime-stabilized soil bases, especially the samples containing coke dust. At 7 days, the 75F25C stabilization reached a UCS value of 5.6 MPa. Under moist curing (MC), the samples ranged from 0.7 MPa to 2.2 MPa for geopolymers with C and from 0.2 MPa to 1.2 MPa for those with B. At 14 and 21 days, all samples continued to gain strength for both types of geopolymers. However,

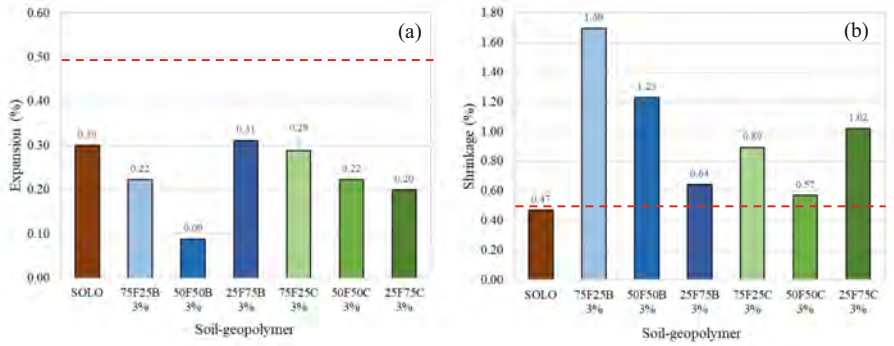


Fig. 1. Results of the Expansion and Shrinkage Tests.

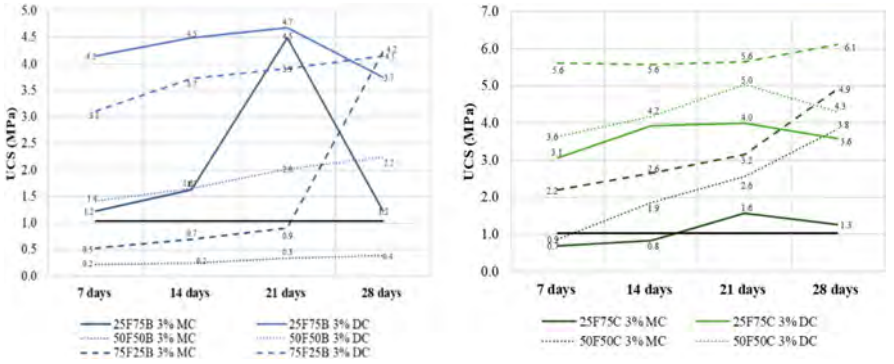


Fig. 2. Unconfined Compressive Strength (UCS) Tests.

after 21 days, some samples began to show reductions in strength. Even so, all samples, except 50F50B-MC, exhibited values above the required minimum.

Samples subjected to dry curing (DC) generally showed more stable and higher strength values from the first 7 days, whereas the strength development of moist-cured samples occurred more gradually over time. Considering strength, shrinkage, and expansion results, the use of samples 25F75B and 50F50C is recommended due to their overall performance, with significant strength gains and lower expansion compared to the others.

4 Conclusion

It can be concluded that the application of geopolymers in soil stabilization represents a technically promising alternative, demonstrating its feasibility for use in road construction projects. However, for more advanced analyses and potential field implementation, further investigations are required, including mechanistic–empirical pavement design analyses and stiffness characterization through laboratory tests such as resilient modulus and fatigue resistance under dynamic loading. These parameters are essential for

evaluating the structural behavior of the material and its long-term performance in pavement base layers. In addition to improving the geotechnical properties of the material, the use of industrial waste as precursors promotes the valorization of by-products, reduces the consumption of natural resources, and minimizes waste disposal in landfills. Furthermore, the reuse of industrial residues contributes to closing material loops and encourages industrial symbiosis strategies, in which waste streams from one sector become valuable inputs for another productive chain. Thus, the proposed solution integrates structural performance and environmental responsibility, establishing itself as a sustainable alternative for pavement engineering while supporting more resource-efficient and low-carbon infrastructure systems.

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Context-Aware Timber Design Across Forested and Non-Forested Regions: Bridging Research and Practice

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Abstract. Timber is increasingly positioned as a cornerstone of sustainable construction, yet its availability, environmental footprint, and design applications vary significantly between forest-rich and forest-limited regions. This study employs a narrative literature review to examine how regional differences in forest resources shape timber supply chains, environmental impacts, and architectural decision-making across selected European contexts. By comparing countries with established forestry industries, such as Austria, Sweden, and Finland, with forest-limited contexts dependent on imports, such as Belgium, the Netherlands, and Denmark, the paper examines how the current literature portrays geography-driven constraints and their implications for environmental performance and architectural design. Synthesizing insights from life-cycle assessment studies, supply-chain research, and socio-technical perspectives, the review identifies critical knowledge gaps between timber resource availability, environmental assessment, and design practice. In response, the concept of context-aware timber design is proposed as a framework that integrates environmental metrics, supply-chain awareness, regional material conditions, and architectural adaptation. The paper argues that bridging research and practice requires not only quantitative assessments but also greater transparency, supply-chain literacy, and design approaches that respond to regional constraints. Ultimately, the study outlines a foundation for context-aware timber design methods suited to both forest-rich and forest-limited regions, supporting more responsible and geographically grounded timber construction.

Keywords: Context-aware timber design · Timber supply chains · Regional disparities · Life-cycle assessment · Timber construction

1 Introduction

The construction sector accounts for a significant share of global greenhouse gas emissions and resource consumption, making the transition toward low-carbon construction materials an urgent priority. Within this context, timber has increasingly been positioned as a promising alternative to conventional building materials due to its renewable nature, relatively low embodied energy, and ability to store biogenic carbon within building

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structures [1, 2]. In particular, mass timber systems such as cross-laminated timber (CLT) and glued laminated timber (glulam) have gained prominence in contemporary architecture and engineering as structural materials capable of replacing steel and concrete in a range of building typologies [3].

The growing interest in timber construction is closely connected to broader sustainability transitions in the built environment, including efforts to reduce embodied carbon, promote circular material use, and advance bio-based economies within the construction sector [4]. Recent studies also emphasize that the climate benefits of timber depend on how wood products are sourced, processed, used, and managed across their life cycle [9–11].

Despite these benefits, the environmental performance of timber construction varies across geographic contexts. Previous studies have shown that the sustainability outcomes of timber construction depend on a range of factors, including forest management practices, processing technologies, transportation distances, substitution assumptions, and end-of-life scenarios [5–7, 10, 11]. As a result, the environmental advantages often attributed to timber cannot be evaluated independently from the regional supply chains through which timber resources are harvested, processed, transported, used, and eventually reused or disposed of.

Across Europe, forest resource availability varies significantly, shaping the way timber is sourced, transported, and applied in construction. While forest-rich countries such as Austria, Sweden, and Finland benefit from established forestry industries, forest-limited countries such as Belgium, the Netherlands, and Denmark rely more heavily on imported timber products [8, 13].

These regional differences raise important questions regarding the environmental implications of timber sourcing and the extent to which timber-based construction strategies developed in forest-rich contexts can be effectively transferred to regions with limited forest resources. While a growing body of research has examined the environmental performance of timber through life-cycle assessment, comparatively few studies address how regional supply chains and resource availability influence architectural decision-making and design strategies.

This study therefore addresses the following research question:

How do regional differences in forest resource availability influence timber supply chains, environmental impacts, and architectural design considerations across European construction contexts?

By examining existing literature on timber supply chains, environmental assessments, and socio-technical dynamics within the construction sector, this paper identifies knowledge gaps between timber resource availability, environmental performance, and architectural practice. The study contributes to the emerging concept of context-aware timber design, which aims to integrate environmental metrics, supply-chain dynamics, and regional resource conditions into design decision-making.

2 Methodology

2.1 Literature Review Approach

This study adopts a narrative literature review approach to investigate how regional forest resource availability influences timber supply chains, environmental impacts, and architectural design practices in Europe. A narrative review is appropriate for this study because the topic is interdisciplinary and draws from environmental assessment, construction management, forestry, architectural design, and socio-technical studies.

2.2 Selection Criteria and Sources

Relevant publications were identified through academic databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. Search queries combined keywords such as "timber construction," "mass timber," "life-cycle assessment," "timber supply chains," "sustainable sourcing," "wood construction in Europe," "forest-rich regions," "forest-limited regions," and "circular timber construction."

The selection process included peer-reviewed journal articles, conference proceedings, and relevant academic or institutional publications written in English. Priority was given to studies published within the last 15 years, especially recent sources from 2020 onwards, focusing on European timber construction, LCA, supply-chain dynamics, forest resource availability, and circular construction.

Publications were initially screened based on titles and abstracts, followed by a full-text review of relevant sources. Additional literature was identified through snowballing, whereby references cited within selected articles were examined to identify further relevant studies.

Following the screening process, approximately 45 peer-reviewed journal articles, conference papers, institutional reports, and policy-related publications were selected for detailed review. The selected literature was analysed thematically through iterative reading and comparison of recurring themes related to timber sourcing, supply-chain structures, environmental assessment, circularity, and architectural design implications. Particular attention was given to differences between forest-rich and forest-limited European contexts and to how these conditions influence sustainability outcomes and design strategies.

2.3 Analytical Scope

The selected literature was analysed through three complementary analytical perspectives. First, LCA studies were examined to understand the environmental impacts associated with timber production, transportation, construction, and end-of-life scenarios. Second, research on timber supply chains was analysed to identify logistical, economic, and governance factors influencing material flows within the construction industry. Third, socio-technical perspectives were considered to understand how relationships among actors, technologies, institutions, certification systems, and procurement practices shape timber construction.

This analytical framework allows the study to examine timber construction not only as a material choice but also as a system shaped by environmental, economic, institutional, and geographical dynamics across different regional contexts.

3 Timber Supply Chains and Regional Contexts

3.1 Timber Production in Forest-Rich European Countries

Countries such as Austria, Sweden, and Finland represent some of the most established timber-producing regions in Europe, supported by strong forestry sectors and developed wood-construction industries [8]. These regions benefit from extensive forest resources, advanced harvesting technologies, established sawmill infrastructures, and integrated industrial networks linking forestry, processing industries, and construction sectors.

The proximity between forest resources, sawmills, and construction markets often results in relatively short supply chains. This spatial closeness can reduce transportation requirements and contribute to lower environmental impacts associated with material sourcing. In addition, established industrial capacity can support wider availability of engineered timber products such as CLT and glulam, making timber construction more accessible to designers and contractors [3, 10].

3.2 Timber Dependence in Forest-Limited Regions

In contrast, forest-limited countries often rely heavily on imported timber products. Belgium and the Netherlands, for example, possess relatively small forest areas and limited domestic timber production. As a result, construction industries in these regions frequently depend on timber sourced from countries with more developed forestry sectors.

These supply chains involve multiple stages including harvesting, processing, transportation, certification, procurement, and distribution across national borders. Consequently, transportation distances and logistical complexities may influence both environmental performance and material costs. Dependence on external supply networks can also introduce uncertainties related to market fluctuations, availability of certified materials, and supply-chain transparency.

For example, timber construction projects in Belgium frequently rely on imported engineered timber products, including CLT panels sourced from countries with stronger production capacity, such as Austria or Germany [13]. While such supply chains enable the adoption of timber construction in forest-limited regions, they also increase dependence on international transportation and external manufacturing networks. This illustrates the importance of integrating supply-chain considerations into design decisions rather than treating timber as a universally equivalent low-carbon material (Table 1).

Table 1. Comparison between forest-rich and forest-limited regions in timber construction.

Aspect	Forest-rich regions	Forest-limited regions
Timber availability	High domestic availability	Dependence on imports
Supply chains	Shorter and more integrated	Longer and more complex
Material traceability	Easier to monitor within established systems	More difficult across borders
Design flexibility	Greater access to local timber systems	More constrained by procurement and availability
Examples	Austria, Sweden, Finland	Belgium, Netherlands, Denmark

3.3 Implications for Construction and Design Practice

The structure of timber supply chains has significant implications for architectural practice. In forest-rich regions, designers may have easier access to locally sourced materials, established industry networks, and standardized timber systems. Conversely, architects in forest-limited contexts may encounter constraints related to procurement processes, supply reliability, certification, material traceability, and transport distances [13].

Despite these regional differences, architectural discourse frequently presents timber construction as a broadly transferable sustainability solution. Such perspectives risk overlooking the spatial, economic, and logistical realities shaping timber availability and environmental performance across different regions. A more context-sensitive approach is therefore needed to connect material sourcing conditions with architectural design decisions.

4 Environmental and Supply-Chain Implications

4.1 Environmental Impacts of Timber Sourcing

Life-cycle assessment studies consistently demonstrate that timber construction can reduce embodied carbon compared to conventional materials such as steel and concrete [5, 6, 9]. However, the magnitude of these benefits depends strongly on sourcing pathways, assumptions about substitution, processing energy, transportation distances, and end-of-life treatment [7, 10, 11].

In forest-rich contexts, locally sourced timber can provide environmental advantages due to shorter supply chains and reduced transportation requirements. Conversely, imported timber products may involve longer transport routes and additional processing stages, which can influence the overall environmental balance of construction projects [7]. This does not mean that imported timber is automatically unsustainable; rather, it indicates that environmental claims must be assessed in relation to specific supply-chain conditions.

4.2 Supply-Chain Complexity and Material Traceability

Another challenge associated with global timber supply chains is the issue of material traceability. Ensuring that timber products originate from sustainably managed forests requires transparent certification systems and reliable documentation procedures. Certification schemes such as FSC and PEFC aim to address these concerns by promoting responsible forest management and supply-chain transparency.

However, certification alone does not resolve all supply-chain challenges. The implementation and effectiveness of certification systems can vary across regions, and the complexity of international supply chains may still limit transparency in certain contexts. For designers and clients, this means that sustainable timber construction requires not only selecting certified materials but also understanding where materials come from, how they are processed, and how procurement decisions influence environmental outcomes.

4.3 Socio-Economic and Governance Dynamics

Beyond environmental considerations, timber supply chains are shaped by governance frameworks, policy incentives, market structures, and industry capabilities. Government policies promoting low-carbon construction can stimulate market demand and encourage innovation in wood-based construction technologies. At the same time, economic conditions, industry capacity, and regulatory environments influence how timber resources are mobilised and integrated into construction practices [12].

These findings suggest that current sustainability narratives surrounding timber construction may oversimplify the relationship between material substitution and environmental performance. While timber is frequently promoted as a sustainable alternative to conventional materials, the literature demonstrates that transportation networks, industrial infrastructures, circularity pathways, and regional resource availability significantly influence environmental outcomes [9–11, 14]. Sustainability assessments based solely on embodied carbon calculations may therefore overlook broader socio-technical and logistical dimensions of timber construction.

5 Toward Context-Aware Timber Design

The findings of this review highlight the need for design approaches that acknowledge regional differences in timber resource availability and supply-chain structures [9–11, 14]. The concept of context-aware timber design is proposed as a framework that integrates environmental assessment, supply-chain awareness, and architectural adaptation.

In practical terms, context-aware timber design involves three interconnected dimensions. First, environmental assessment considers sourcing, processing, transportation, use, and end-of-life pathways. Second, supply-chain awareness concerns procurement networks, traceability, certification, and regional availability of timber resources. Third, architectural adaptation refers to design decisions that respond to locally available materials, regional construction capacities, and environmental constraints.

This framework shifts the role of architects from selecting timber as a generic sustainable material toward evaluating the specific conditions under which timber becomes environmentally and regionally appropriate. This is particularly important in forest-limited contexts, where design decisions may have stronger implications for procurement, transportation, and supply-chain dependency.

6 Discussion

The findings of this review highlight a persistent gap between environmental assessment research and architectural decision-making. Existing studies often evaluate the carbon mitigation potential of timber through LCA methods [5, 6, 9], but give less attention to how regional supply-chain structures and forest resource availability shape the feasibility of timber construction.

This review suggests that timber cannot be treated as a universally transferable sustainability solution. Its environmental and logistical implications depend strongly on regional resource conditions, transportation pathways, certification systems, and procurement networks. In forest-rich regions, local resources and established industries may support shorter supply chains and stable material availability. In forest-limited regions, reliance on imported timber can create more complex supply networks, affecting traceability, cost, and environmental performance [7, 13].

For architectural practice, this means that timber design should be connected to supply-chain literacy. Sustainable timber construction in forest-limited contexts may require alternative sourcing strategies, closer collaboration with manufacturers and suppliers, and design decisions that respond to regional constraints rather than assuming timber is automatically low-carbon.

7 Conclusions

This paper examined how regional forest resource availability influences timber supply chains, environmental impacts, and architectural decision-making across selected European contexts. The review shows that timber's sustainability performance depends not only on material substitution benefits, but also on supply-chain structures, transportation pathways, industrial capacity, certification, and governance conditions.

The study identifies a gap between environmental assessment research and the practical realities of architectural design in forest-limited regions. In response, context-aware timber design is proposed as a framework integrating environmental assessment, supply-chain awareness, and regional material conditions into design decision-making.

By emphasizing supply-chain literacy and geographically grounded design strategies, this approach supports a more nuanced understanding of timber construction as a material system embedded within broader socio-economic and environmental networks.

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Manufacturing of Earthen Specimens: Towards Standardised Compressive Strength Testing

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Abstract. The mechanical characterisation of earthen materials is essential for their use in load-bearing construction. However, standardised procedures for compressive strength testing are still lacking, especially for materials such as poured earth (PE), rammed earth (RE), and compressed earth blocks (CEBs). Based on a literature review the paper identifies parameters influencing the compressive strength during the manufacturing process, such as manufacturing moisture content (MMC), the applied compaction method and energy, and formwork characteristics. The study consolidates international recommendations, evaluates the suitability of established soil mechanics and concrete testing procedures, and highlights unresolved methodological gaps, particularly concerning the MMC and compaction methods. Based on this evaluation, the paper proposes harmonised documentation requirements and procedural recommendations aimed at improving the reproducibility and comparability of earthen material testing. While the findings do not yet establish a uniform manufacturing protocol, they represent an essential step toward a standardised compressive strength testing of RE, PE and CEBs.

Keywords: Earthen Materials · Standardisation · Specimen Manufacturing · Compressive Strength

1 Introduction

In recent years, load-bearing earthen construction has experienced a renewed momentum. Alongside innovations such as poured earth and 3D printing [1], established techniques like rammed earth and earth block masonry are once again gaining global attention [2]. This revival is primarily driven by the low carbon footprint and full recyclability of earthen materials [3].

Despite these advantages, load-bearing earthen structures remain a niche application. A key barrier to wider implementation is the absence of standardised structural design

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frameworks that reflect the state of the art and ensure reliable planning and execution. The development of such frameworks relies on standardised testing procedures. This applies particularly to compressive strength, which represents the most critical mechanical property in load-bearing design. Standardised test methods enable the generation of consistent datasets for determining characteristic values and partial safety factors, forming the basis of semi-probabilistic design approaches. Moreover, they ensure quality control and are therefore essential for improving the competitiveness of earthen construction compared to conventional materials such as concrete.

In Germany, some earthen building materials are already standardised, for example, earth blocks acc. to DIN 18945 [4] and earth masonry mortar acc. to DIN 18946 [5]. However, for rammed earth (RE), poured earth (PE), and compressed earth blocks (CEBs) with dimensions deviating from [4], no normative regulations currently exist. Baier et al. [6] therefore compiled recommendations for compressive strength testing of these materials, drawing on existing literature, international standards, and practical experience. Their work discusses aspects applicable to all the above-mentioned earthen materials. They recommend, for example, using cylindrical specimens with an aspect ratio of h/d = 2.0 to reduce lateral constraint effects and ensure homogeneously compacted specimens (see Fig. 1). Additional recommendations address specimen size, conditioning, type of loading, and loading rate.

The present paper complements Baier et al. [6] by addressing the unresolved topic of specimen manufacture for RE, CEBs, and PE. In general, the mechanical properties of earthen materials are significantly influenced by manufacturing moisture content (MMC), compaction energy and method [7]. Consequently, defined manufacturing procedures are essential to guarantee the comparability of test results. The paper consolidates requirements from international standards for earthen materials, such as NZS 4298 [8], as well as literature data regarding homogenisation, manufacturing moisture, compaction methods, and other relevant parameters. It identifies where existing standards for RE, PE, and CEBs lack precision and explores how adapted procedures from related disciplines, such as concrete and soil testing, may be transferred to earthen materials. Finally, the paper formulates recommendations to strengthen the understanding of key parameters in specimen preparation. However, these recommendations do not yet constitute a standardised manufacturing protocol, as several influencing factors still require further investigation.

The paper builds on the on-going efforts of the working group *Forschung* within the *Dachverband Lehm e.V.*. The group aims to establish a unified compressive strength testing regime for not yet standardised earthen materials within the DACH-region.

2 Manufacturing of Earthen Specimens

2.1 Homogenisation of Earthen Material

Homogenisation serves two main purposes. First, it promotes a uniform particle-size distribution. Second, it equilibrates moisture at particle surfaces and within capillary inter- and intra-aggregate porosity. Both are prerequisites for reproducible compaction behaviour. To facilitate moisture equilibration throughout the mixture, e.g., DIN 18127

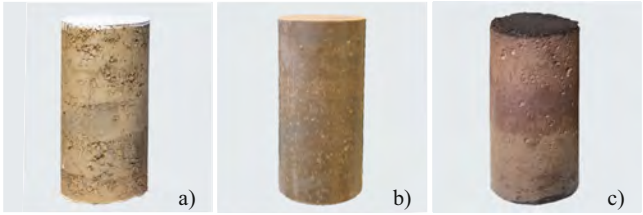


Fig. 1. Cylindrical test specimens with an aspect ratio of h/d = 2.0 - a) RE, b) CEBs, and c) PE

[9] recommends adjusting the moisture content at least 24 h prior to specimen preparation. Over this period, moisture redistributes into the microporous particle network, establishing a stable moisture state that is critical for reproducible mechanical response [10]. If the initial moisture content is excessive, the material should be air-dried until the target value is reached.

To the authors' knowledge, no systematic studies are available that quantify the influence of homogenisation (e.g. type, intensity, and duration of mixing as well as duration of soaking) on the compressive strength of rammed earth, poured earth, or compressed earth blocks. Consequently, homogenisation should be performed to a level that minimises specimen-to-specimen variability and yields sufficiently low standard deviations in mechanical test results.

2.2 Manufacturing of Rammed Earth (RE) Test Specimen

Manufacturing Moisture Content. The MMC strongly affects the dry density and thus the compressive strength of RE. Preliminary results by Baier et al. [11] indicate that even minor variations of 0.5 wt.% in MMC can reduce compressive strength by up to 25%-points.

Most studies presented in the literature, e.g. [12, 13], as well as international standards, such as NZS 4298 [8], employ the Proctor test to determine a suitable MMC for rammed earth. The Proctor test, as defined in DIN 18127 [9], is a standard procedure in soil mechanics. It identifies the optimum moisture content (OMC) at which the maximum dry density (ρ_{Pr}) is achieved under a given compaction energy. The standard Proctor test applies a compaction energy of 0.6 MJ/m^3. The modified Proctor test applies a substantially higher compaction energy of 2.6 MJ/m^3, resulting in a lower OMC.

However, the literature provides no consensus on whether the standard or the modified Proctor test is more suitable for determining the optimum MMC of rammed earth. NZS 4298 [8] specifies a target MMC within $OMC_{Standard} \pm 3$ wt.%. Considering the sensitivity shown in [11], a range of ± 3 wt.% appears overly broad. Keable & Keable [14] argue that the standard Proctor test applies mainly to hand ramming, while pneumatic or mechanical rammers require the modified Proctor test. Based on the authors' experience, however, the modified Proctor test tends to result in mixtures that are too dry, and the optimum MMC for rammed earth often lies between the $OMC_{Standard}$ and $OMC_{Modified}$. Further research is required to determine whether the Proctor test is appropriate for defining an adequate MMC for RE construction.

On construction sites, a suitable MMC is usually not determined gravimetrically but by simple tests such as the Drop Test described in NZS 4298 [8]. In this method, a ball is formed and dropped from a height of approximately 1.5 m. A suitable MMC is indicated when the ball breaks into several lumps upon impact. If it remains largely intact, the MMC is too high. If the ball crumbles into powder or cannot be shaped at all, the MMC is too low. Based on the authors' experience, this test is sufficient to establish an appropriate MMC for RE specimens. In general, the MMC should be documented, e.g. in accordance with DIN EN ISO 17892-1 [15].

Compaction Method, Compaction Energy, and Layer Thickness. To ensure a controlled compaction energy resulting in densities with low variance, many studies use a Proctor hammer or automated Proctor compaction device (e.g. in [13]). Due to the defined number of blows, drop weight, and drop height, a uniform compaction can be ensured for cylindrical specimens. Baier et al. [11] demonstrate that the compaction energy of the standard Proctor test is sufficient to produce representative specimens.

Based on this, the authors recommend conducting the compaction process preferably using an automatic Proctor device adopting the parameters listed in Table 1. The number of layers follows the loose layer thickness, which should range between 10 cm and 15 cm according to NZS 4298 [8]. With a layer thickness of approximately 10 cm, the parameters in Table 1 achieve a compaction ratio of about 2/3 of the initial layer thickness, which represents a sufficient compaction in RE construction [16]. Following DIN 18127 [9], at least three layers should be compacted. To guarantee an even layer thickness, an extension ring is required, such as that used for a Proctor mould. In accordance with [9], no more than 1 cm of material should protrude beyond the formwork edge. Excess material can be removed using a lattice plane grid float.

Table 1. Recommended compaction energies and parameters for cylindrical RE test specimen

Size of cylinder	Weight of hammer	Drop height	No. of blows	No. of layers	Loose layer thickness	Resulting compaction energy
Ø100 mm/200 mm	4.5 kg	30 cm	25	3	10 cm	0.6 MJ/m^3
Ø150 mm/300 mm	4.5 kg	45 cm	32	5	9–10 cm	0.6 MJ/m^3

If other compaction methods or specimen geometries are used, the compaction procedure should be documented. The authors recommend complying with a loose layer thickness of 10–15 cm and achieving a compaction ratio of at least 2/3. Further guidance of whether test specimens are sufficiently compacted can be found in NZS 4298 [8], which specifies a minimum dry density of $\rho_{dry} \geq 0.98 \cdot \rho_{Pr}$ for test specimens.

In all cases, the density right after manufacturing (ρ_0) and the dry density (ρ_{Dry}) should be documented. The latter is obtained from ρ_0 and the MMC by Eq. (1). Further research should focus on to what extent different compaction methods and energies

influence the compressive strength of RE.

$$\rho_{\mathrm{Dry}} = \rho_0/(1 + \mathrm{MMC}) \tag{1}$$

2.3 Manufacturing of Compressed Earth Blocks (CEBs) Specimen

Manufacturing Moisture Content. As in RE construction, the MMC strongly governs the manufacturing of compressed earth blocks (CEBs). During pressing, the material is densified under high stress to promote a tight grain structure. This is achieved by minimising the pore volume occupied by air and water. The moisture content at the time of specimen manufacture can either facilitate or impede densification. Relative to the Proctor test, the optimum MMC for CEBs may be markedly lower than the OMC determined by both the standard and the modified Proctor test in accordance with [9]. This reflects the higher compaction energy imparted by pressing stresses compared with the Proctor procedure. For CEBs, the MMC should be reported alongside the dry density achieved during manufacture (see Eq. 1). The optimum MMC should be established and optimised for each material formulation and forming route. Based on the authors' observations, additives can shift the optimum MMC substantially.

Compaction Stress and Compaction Duration. Two primary process parameters govern CEB production: the applied compaction stress and the compaction duration. A defining characteristic of the method is the high stress applied during pressing. Current industrial practice uses pressing stresses of <12.5 MPa [17]. Previous work explored substantially higher stresses (up to 400 MPa) and their effect on the compressive strength [17–19]. Under otherwise constant manufacturing conditions, higher compaction stress increases dry density and, in turn, compressive strength. A comparable trend has been reported for compaction duration. An increasing dry density with longer dwell time under sustained pressure was observed [17, 19]. Key descriptors to be documented are the loading rate (v_0), the maximum compaction stress (σ_0), and the dwell time at σ_0 (t_0), as well as the displacement rate required to maintain σ_0. However, due to the wide range of reported operating parameters, a comprehensive manufacturing protocol cannot be provided.

Mould Characteristics and Homogeneity of Dry Density. Compressive strength is also influenced by boundary conditions during pressing. Mould characteristics and the specimen-manufacture setup can introduce density gradients. Figure 2 illustrates an example setup in which cylindrical CEB specimens are produced in a steel mould. The material is compacted by a plunger under an applied force F_0. Depending on the MMC and the surface condition of the mould's inner wall, substantial friction losses were observed, reducing the transmitted force F_A at the bottom of the mould. In the authors' experience, F_A can be substantially (10–90%) lower than F_0. Friction-induced stress losses imply decreasing compaction along the pressing direction. A reduction in compressive strength is therefore expected due to locally lower dry density. Future work should quantify this effect and account for it, for example through correction factors. The specimen-manufacturing setup should be documented in detail in test protocols, including the mould surface condition. The same issue applies to double-sided compaction.

In that case, the minimum compaction, and thus the minimum dry density, would be expected at mid-height of the specimen.

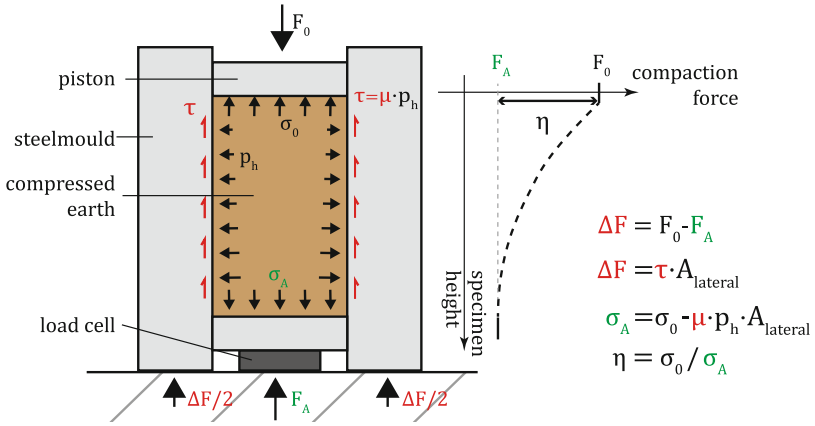


Fig. 2. Cylindrical mould for CEB manufacture showing friction-induced stress losses.

2.4 Manufacturing of Poured Earth (PE) Test Specimen

Manufacturing Moisture Content. In PE, the MMC is a key control parameter, as it directly governs flowability during casting as well as material performance after drying.

In the absence of earthen-specific classifications, standards for concrete testing are adopted to ensure comparability. In this paper, PE is defined by its fresh-state consistency, corresponding to consistency classes F3–F6 according to DIN EN 206 [20] or a flow diameter > 420 mm as specified in DIN EN 12350-5 [21]. Slump tests in accordance with DIN EN 12350-2 [22] may be used as an alternative indicator, with values of approximately 5.2 cm reported for PE [23, 24].

The moisture content required to achieve a pourable consistency depends strongly on the earth's Atterberg limits, particularly the liquid limit, which has been reported to range from 42.0% to 75.7% for different soils [23, 24]. This variability directly affects the moisture demand for liquefaction. However, if pourability is achieved solely by increasing the MMC, prolonged drying times, shrinkage cracking, and reduced dry density represent major challenges.

For this reason, liquefaction is often supported by additives such as dispersants or stabilisers [1, 25]. The use of additives can mitigate these effects but may adversely affect vapour sorption, recyclability, and the carbon footprint of the material [26, 27]. For some additive-liquefied mixtures, reported MMCs range from 15% to 40% [1, 28].

Compaction Process. In contrast to other earthen construction techniques, PE can be compacted with relatively low effort, for example by vibration using a vibrating table or internal vibrators such as poker or needle vibrators [1, 24]. As the effects of different compaction procedures on compressive strength remain insufficiently investigated,

no clear recommendation can yet be provided. Until further research is available, compaction is therefore recommended to follow DIN EN 12390-2 [29]. In general, the specimen-manufacturing setup should be documented in detail in test protocols.

3 Conclusion

The evaluation of the available findings demonstrates that manufacturing-related process parameters significantly influence the compressive strength of specimens made of rammed earth (RE), compressed earth (CEB), and poured earth (PE). Across all materials, the manufacturing moisture content (MMC) is a key parameter and therefore should always be reported (e.g., according to DIN EN ISO 17892-1 [15]). In addition, the dry density of the test specimens, determined by Eq. (1), should be reported.

For RE specimens, the use of an automatic Proctor compaction device or a Proctor hammer for specimen manufacturing provides a controlled compaction energy and enhances reproducibility. Table 1 provides recommendations regarding compaction parameters. Further research is required to determine an adequate MMC for RE. At present, the authors recommend determining a suitable MMC through the Drop Test according to NZS 4298 [8].

For CEB specimens, the wide range of compaction stresses reported in the literature precludes a comprehensive manufacturing protocol. To compare results, the applied compaction stress, compaction duration, loading rate, and dwell time, as well as the surface condition of the mould should be recorded. An adequate MMC should be optimised for each material composition and compaction setting.

The compaction process for PE specimens may follow concrete standards, such as DIN EN 12390-2 [29]. In general, the MMC should be kept as low as possible to minimise shrinkage cracking and to achieve higher compressive strength. To ensure comparability between research results, consistency class in accordance with DIN EN 206 [20] and flow diameter (according to [21] or [22]) should be reported.

The recommendations formulated above represent a step toward improving the comparability of test results across laboratories and research groups. However, a universally applicable manufacturing protocol cannot yet be established, as systematic experimental investigation into the influencing factors identified herein is still needed. The present work is therefore intended as a contribution to an ongoing research dialogue, and the authors encourage continued investigation and publication in this field.

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Pigments from Green Seaweed *Ulva* spp. for a Potential Circular Bio-Based Building Application

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Abstract. *Ulva*, a widely distributed green macroalga with high pigment content and rapid growth, represents a promising renewable source of bio-based colorants. Natural pigments, such as chlorophylls and carotenoids, have numerous applications in various fields, including the food, cosmetic, and textile industries, as well as in biomedical applications. They can also serve as completely innovative solutions for environmental building technologies, offering bio-based and sustainable alternatives to conventional synthetic pigments, to create eco-friendly coatings and finishes that reduce reliance on synthetic chemicals. Pigments derived from the seaweed *Ulva* offer sustainable colorants or other green construction materials. The study quantified pigments extracted from *Ulva* spp. to determine levels of chlorophyll *a*, chlorophyll *b*, and total carotenoids, assessing their potential within circular economy frameworks, especially those aligned to the built environment. Chlorophylls give a characteristic green hue, while carotenoids enhance photostability and antioxidant properties, making these compounds appealing for use in bio-based coatings, biopolymer composites, and eco-friendly decorative materials. Extraction from green macroalgae facilitates the development of color-stable, low-toxicity, sustainable alternatives to synthetic pigments. Additionally, using pigments from macroalgal biomass promotes resource valorization and waste reduction, supporting circular strategies through the use of rapidly renewable, raw materials. Overall, pigments derived from *Ulva* offer a viable pathway toward greener building materials, reinforcing the shift toward circular and bio-based practices in the construction industry.

Keywords: green macroalgae · Ulva · green pigments · circular economy · sustainability · built environment

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1 Introduction

The global transition toward sustainable development has profoundly reshaped contemporary production and consumption systems, placing circular economy principles at the center of industrial innovation [1]. In contrast to linear economic models, circular economy frameworks emphasize resource efficiency, material recovery, extended product lifecycles, transparency across value chains, and waste and underutilized products valorization [1, 2]. Colorants and pigments represent a critical yet often underestimated component of product design. Synthetic pigments are extensively used across sectors such as food, cosmetics, textiles, packaging, and construction materials due to their cost-effectiveness, color stability, and ease of standardization. However, mounting evidence highlights their environmental persistence, potential toxicity, and contribution to pollution across the production, use, and disposal phases [3, 4]. These concerns have intensified regulatory inspection and raised consumer awareness regarding the origin and safety of colorants, particularly in products with direct human exposure.

In response, natural pigments derived from renewable biological sources have gained increasing attention as sustainable alternatives [5]. Beyond their coloring capacity, many natural pigments exhibit functional properties, including antioxidant activity, UV protection, and bio-compatibility, which can enhance product performance and longevity [6, 7]. The integration of such multifunctional materials aligns with principles of green chemistry and the circular economy, while maintaining safety and functionality. Marine biomass has emerged as a particularly promising source of natural pigments within circular bio-economy models. Unlike terrestrial plants, marine organisms do not compete for arable land or freshwater resources and often exhibit rapid growth rates and high biochemical diversity [8, 9]. Macroalgae represent an abundant and renewable resource with significant yet underexploited potential for sustainable material innovation [10]. Among marine macroalgae, species belonging to the genus *Ulva* (Chlorophyta) occupy a unique position. *Ulva* spp. is a globally distributed green macroalgae characterized by fast growth, high photosynthetic efficiency, and adaptability to nutrient-rich coastal environments [10]. While excessive proliferation of *Ulva* biomass is frequently associated with environmental challenges, this same biomass constitutes a valuable reservoir of pigments, polysaccharides, proteins, and bioactive compounds [11, 12]. Reframing *Ulva* from an ecological burden to a resource aligns with circular economy strategies focused on waste valorization and sustainable material sourcing. Natural pigments extracted from *Ulva* spp., primarily chlorophylls and carotenoids, have attracted growing scientific and industrial interest due to their coloring properties and biological functionality [5]. Importantly, pigment composition and concentration are influenced by environmental and geographical factors, underscoring the relevance of region-specific studies and localized valorization approaches [13, 14]. Such localization is particularly relevant in European countries, where the sustainable use of regional resources can support equitable development and resilience. Incorporating *Ulva*-derived pigments into innovative products, therefore, connects material innovation supporting sustainable production and consumption practices. Within this context, the present study explores the potential of *Ulva* spp. as a sustainable source of natural pigments, positioned at the intersection of

marine biotechnology and circular product design, with potential applications in building construction. By integrating green extraction principles, this work contributes to the broader discourse on sustainable material solutions.

2 Biological and Ecological Characteristics, Biochemical Composition, Pigments Profile, and Reframing Within Circular Economy Models of *Ulva* spp.

The genus *Ulva* comprises green macroalgae widely distributed along temperate and tropical coastlines [10]. Characterized by rapid growth rates, high photosynthetic efficiency, and remarkable adaptability to varying environmental conditions, *Ulva* spp. bloom in nutrient-rich coastal waters and is one of the most abundant marine macroalgae globally. Traditionally, excessive proliferation of *Ulva* has focused on management strategies that involve removal and disposal, reinforcing the perception of *Ulva* as waste biomass. From a circular economy perspective, this approach represents an opportunity. The biochemical richness of Ulva biomass suggests significant potential for valorization pathways. Ulva spp. has been characterized by a diverse pigment composition, primarily dominated by chlorophylls and carotenoids, which play essential roles in photosynthesis and photoprotection [5]. Chlorophyll a and b present the characteristic green coloration, while accessory pigments such as lutein, β-carotene, and other carotenoids contribute to light-harvesting efficiency and oxidative stress mitigation [15]. These pigments are of increasing interest not only for their coloring properties but also for their functional attributes, including antioxidant activity and photostability. Such multifunctionality aligns well with contemporary design requirements, where materials are expected to deliver both aesthetic and performance-related benefits. The Ulva biomass represents a renewable, locally available resource that can be reintegrated into material through processing strategies [10]. Valorizing Ulva for natural pigment production offers multiple circular benefits: reduction of environmental pressure associated with algal blooms, substitution of synthetic pigments, and creation of bio-based materials. Moreover, when combined with green extraction technologies, this approach minimizes energy consumption and solvent use, further enhancing sustainability [16].

3 Materials and Methods

3.1 Collection and Preparation of Ulva Biomass

Fresh biomass of *Ulva* spp. (Figure 1) was collected from coastal areas of two Mediterranean regions: selected sites along the Italian coastline (Civitanova, Marche region) and the Montenegro Adriatic coast (Boka Kotorska Bay), in July 2025. Sampling locations were selected based on ecological relevance, the availability of biomass, and the absence of visible industrial contamination, to ensure representative and comparable material. The collected algal material was manually cleaned on-site to remove epiphytes, sand, and associated fragments, followed by thorough rinsing with seawater.

Upon transport to the laboratory, samples were washed with distilled water to remove residual salts and impurities. Biomass was subsequently air-dried under controlled conditions or subjected to low-temperature drying to minimize pigment degradation. Dried samples (Fig. 1) were milled to a homogeneous particle size and stored in airtight containers protected from light and moisture until further analysis. In addition to the previously analyzed material, the bioactive compounds composition of *Ulva* biomass sampled in July 2024 from the Montenegro coast (the same location, Boka Kotorska Bay), was also investigated. A comparative analysis of pigments and other bioactive components was conducted between two *Ulva* samples collected from the same coastal locality in Montenegro but analyzed at different time points. The objective of this comparison was to evaluate the effect of storage duration and conditions on the stability of pigments and selected bioactive compounds over 1 year. Both samples originated from the same harvesting site and were subjected to identical post-harvest processing. Following collection, the biomass was air-dried and stored for 1 year in plastic bags, protected from light and kept at ambient temperature. By minimizing variability related to geographic origin and environmental exposure, this experimental design enabled a focused assessment of changes in pigment content and bioactive profiles attributable specifically to storage conditions and storage time.



Fig. 1. Fresh vs. dried *Ulva* spp.

3.2 Green Extraction of Natural Pigments

Pigment extraction was performed using an environmentally friendly methodology consistent with green chemistry principles, as previously examined by Ćujić Nikolić et al. 2025b [10]. The extraction technique employed was maceration, with a process duration of 2 h, a solid-to-solvent ratio of 1:20, and a 50% ethanol-water mixture (w/w). Emphasis was placed on minimizing solvent toxicity, energy consumption, and processing time, while ensuring efficient recovery of chlorophylls and carotenoids. Extraction protocols were adapted from a previously published method by Ćujić Nikolić et al. 2025b [10], with minor modifications to optimize yield and stability. Briefly, milled *Ulva* biomass was subjected to solvent extraction using low-toxicity solvents under controlled temperature and agitation conditions. Extracts were subsequently filtered. The choice of extraction conditions was guided by the dual objective of maximizing pigment recovery and ensuring suitability for downstream applications in sustainable production.

3.3 Pigment Analysis and Quantification

The qualitative and quantitative analysis of Ulva-derived pigments focused primarily on chlorophyll a, chlorophyll b, and total carotenoids. Spectrophotometric methods were

employed for pigment determination, using established equations and absorption coefficients previously reported [5, 15]. Absorbance measurements were conducted at characteristic wavelengths corresponding to chlorophylls and carotenoids. Pigment concentrations were calculated and expressed relative to dry biomass weight. All measurements were performed in triplicate, and results were reported as mean values.

3.4 Total Polyphenol Analysis

For total polyphenols determination, a Folin-Ciocalteu assay with slight modifications was applied by the Waterman and Mole method. The 200 μL sample (*Ulva* extracts) was mixed with the addition of 1000 μL of 10% Folin-Ciocalteu reagent, and after 4 min, 800 μL of 7.5% Na_2CO_3 was added to the reaction mixture. Blank control contained distilled water instead of a sample in the reaction mixture. The samples were incubated in the dark for 2 h, and after that, absorbance was measured at 765 nm. Obtained results of polyphenol content for extracts as milligrams of gallic acid equivalent per gram of *Ulva* dried biomass (mg GAE/g) [5].

Comparative analysis was conducted to evaluate differences in phytochemical content between *Ulva* samples originating from Italy and Montenegro. The obtained results were contextualized through comparison with data reported in the existing literature on *Ulva* spp. pigments, enabling assessment of regional variability and potential implications for sustainable valorization strategies.

4 Results and Discussion

4.1 Pigment Profile and Composition of Ulva spp.

Analysis of *Ulva* spp. extracts confirmed the presence of chlorophyll *a* and *b* as dominant pigments, accompanied by total carotenoids. This pigment composition is consistent with the photosynthetic characteristics of green macroalgae and aligns with previously reported profiles for *Ulva* species from diverse geographic regions [17, 18]. The relative abundance of chlorophylls and carotenoids highlights the strong potential of *Ulva* biomass as a natural pigment source, particularly for applications requiring intense coloration combined with functional properties such as antioxidant activity. The pigment profile identified in *Ulva* spp. biomass from both Italy and Montenegro is consistent with the characteristic composition reported for green macroalgae, where chlorophyll *a* and *b* represent the dominant pigments, accompanied by lower but significant levels of carotenoids. Similar pigment distributions have been reported for *Ulva lactuca* and related species collected from the Mediterranean, Atlantic, and Asian coastal regions [13, 14]. Reported chlorophyll contents in *Ulva* spp. vary widely depending on environmental conditions, seasonality, and analytical methodology. Previous studies have documented chlorophyll concentrations ranging from moderate to high values in Mediterranean *Ulva* populations, particularly in nutrient-rich coastal waters [11, 23]. The pigment levels observed in the present study fall within this reported range, confirming the representativeness and comparability of the analyzed biomass. Carotenoid content in *Ulva* has generally been reported at lower levels compared to brown and red macroalgae; however,

their functional importance remains significant due to their antioxidant and photoprotective roles. Studies by Holdt and Kraan (2011) and Stengel and Connan (2015) [13, 14] highlight lutein and β-carotene as predominant carotenoids in green macroalgae, as confirmed in the author's research [5]. The growing body of literature on natural pigments from marine macroalgae underscores their potential as sustainable alternatives to synthetic colorants. Compared to synthetic pigments, which are associated with high environmental persistence and potential toxicological concerns [3, 4], Ulva-based pigments offer a biodegradable and renewable alternative. Moreover, their extraction using green methodologies aligns with recommendations from recent reviews emphasizing the importance of low-impact processing in sustainable pigment production [7].

4.2 Comparative Pigment and Polyphenols Content: Italy vs. Montenegro Adriatic Coast

Comparative evaluation revealed discernible differences in pigment content between *Ulva* samples collected from the coastal areas of Italy and Montenegro. Variations were observed in the relative concentrations of individual pigments and were 216.253, 220.686, and 33.243 μg/g from chlorophylls a, b, and carotenoids for *Ulva* biomass sampled in Montenegro, and 156.124, 168.723, 44.785 μg/g chlorophylls *a, b*, and carotenoids from *Ulva* biomass originated from the Italian Adriatic Coast.

The polyphenol content demonstrated 0.6764 mg GAE/g of dried Montenegro *Ulva* biomass compared to 0.4972 mg GAE/g of dried Italy *Ulva* biomass. These differences can be attributed to site-specific environmental factors, including nutrient availability, light exposure, water temperature, and seasonal growth conditions. Such variability underscores the importance of localized biomass characterization when designing region-specific valorization pathways [18]. Importantly, the observed pigment levels in both regions fall within the range reported in the literature for *Ulva* spp., confirming the suitability of the studied biomass for pigment extraction and further applications [19].

The differences observed between *Ulva* samples from Italy and Montenegro agree with earlier reports emphasizing the influence of geographic and environmental factors on pigment accumulation. Factors such as light intensity, nutrient availability, water temperature, and hydrodynamic conditions have been shown to significantly affect pigment biosynthesis in macroalgae [20, 21].

Comparative studies conducted across different Mediterranean regions indicate that even within relatively small geographic distances, *Ulva* spp. can exhibit notable variability in pigment content [22]. Importantly, the pigment content recorded in both country samples remains comparable to, or exceeds, values reported in several studies on *Ulva* biomass collected for biotechnological applications [11, 23], supporting the suitability of both regions as sources of natural pigments. Several studies have highlighted that natural pigments, including chlorophylls and carotenoids, can impart functional benefits such as antioxidant capacity and UV protection, which are absent in most synthetic dyes [6, 7]. These properties are particularly relevant for products designed for prolonged use, as oxidative degradation is a key factor limiting product longevity.

4.3 Effect of One-Year Storage on Pigment and Bioactive Compound Stability in Ulva Biomass

A comparative analysis was conducted between two *Ulva* biomass samples collected from the same coastal region in Montenegro, with a one-year interval between harvesting. This approach enabled assessment of the influence of prolonged storage conditions on pigment composition and bioactive compounds, while minimizing variability associated with geographic origin and environmental factors.

The results revealed a clear differential stability among pigment classes following 1 year of storage. The total chlorophyll content in the stored biomass decreased markedly, with measured values of 168.668 and 146.240 μg/g of dried *Ulva* biomass, sampled in 2024 and 2025, respectively, indicating a reduction in green pigments. This decline is consistent with the well-documented sensitivity of chlorophylls to external factors such as oxygen exposure, residual moisture, and thermal conditions during storage. Chlorophyll degradation during prolonged storage has been widely reported in algal and plant biomasses and is primarily attributed to oxidative and photochemical processes, even when samples are protected from direct light. In contrast, carotenoid content remained remarkably stable, with a measured value of 33.562 μg/g of dried biomass after 1 year of storage. This finding demonstrates the high resistance of carotenoids to degradation under the applied storage conditions, confirming their known stability and antioxidative properties. The preservation of carotenoids observed in this study aligns with previous reports that highlight their superior stability relative to chlorophylls in dried algal matrices [5]. Importantly, despite the observed reduction in chlorophyll content, the overall pigment levels in the stored biomass from Montenegro remained high. The retained pigment concentrations were comparable to those measured in *Ulva* samples collected in Italy, underscoring the strong potential of stored biomass as a valuable source of natural pigments. This observation is particularly relevant for circular bio-economy models, where seasonal harvesting and extended storage of marine biomass are often unavoidable. The total phenolic content of the one-year stored sample was determined to be 0.4818 mg GAE/g, a value that was nearly identical to the total phenolic content measured in fresh biomass from Italy. This result indicates that phenolic compounds exhibit high stability during long-term storage under the applied conditions, further supporting the suitability of *Ulva* biomass in the context of natural antioxidants. Given the recognized antioxidant activity of phenolic compounds, their preservation reinforces the functional value of stored biomass for functional material applications. The alignment of Ulva-based pigment production with eco-labeling and transparency frameworks responds to calls in the literature for greater integration of material science innovations [9, 24].

5 Conclusions

This study highlights the potential of *Ulva* spp. as a sustainable and underutilized marine resource for the production of natural pigments and polyphenols within circular economy frameworks, supporting innovation in bio-based building materials. The results demonstrated the applicability of Ulva-derived extracts as bio-based additives for architectural coatings, bio-polymer composites, and eco-friendly finishing materials used

in the built environment. The presence of chlorophylls, carotenoids, and polyphenols suggests additional functional benefits beyond coloration, including UV-protective and antioxidant effects, which may contribute to improved durability and oxidative stability of sustainable construction materials. The observed pigment stability after one-year storage further supports the feasibility of seasonal biomass valorization and industrial-scale implementation in circular construction material supply chains. These findings provide an initial experimental basis for future engineering validation involving compatibility testing, mechanical performance assessment, weathering resistance, and long-term stability of Ulva-based pigments incorporated into building materials. The study moves beyond conceptual circularity by providing experimentally validated pigment compositions relevant for the development of renewable, low-toxicity functional materials for sustainable building applications. The use of natural pigments resonates with growing consumer demand for products perceived as healthier, safer, and environmentally responsible.

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Mechanical and Durability Performance of Concrete with Low-Quality Recycled Aggregates

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Abstract. The use of recycled aggregate (RA) in concrete production offers a sustainable solution to reduce natural aggregate (NA) consumption and construction waste. However, incorporating low-quality RA can compromise mechanical and durability properties. This study investigates the performance of concrete mixtures made with RA sourced from a recycling plant, classified as low quality. Three mixtures were prepared for exposure class XC1 according to ÖNORM B 4710-1: a reference mixture with 100% NA (XC1-0), and two mixtures with 25% (XC1-25) and 65% (XC1-65) RA replacement by volume. To keep a constant water-to-cement ratio of 0.69, RA was pre-wetted to 80% of its water absorption capacity. The properties of fresh and hardened concrete were evaluated through density, compressive strength, modulus of elasticity, and accelerated carbonation tests. The results show a consistent decline in density and mechanical performance with increasing RA content. Fresh density decreased from 2359 to 2249 kg/m^3, while 28-day compressive strength decreased from 42.3 MPa to 37.0 MPa, and elastic modulus reduced from 34.3 GPa to 31.8 GPa. Carbonation depth increased from 7.7 mm to 10.0 mm at 28 days and from 12.5 mm to 16.0 mm at 70 days, indicating higher permeability and reduced CO_2 resistance. Despite moderate performance reductions, the investigated mixtures demonstrated the potential of low-quality RA for sustainable concrete production.

Keywords: Recycled Concrete Aggregate · Mechanical Properties · Durability · Carbonation · Sustainable Concrete

1 Introduction

The intensive extraction of non-renewable natural resources for producing concrete aggregates, such as sand and gravel, leads to significant resource depletion and ecological degradation. At the same time, the demolition of ageing infrastructure contributes to the generation of vast quantities of construction and demolition waste (CDW) on a global scale [1]. One widely accepted approach for managing CDW is its utilization as a source of aggregates. In this method, solid waste, such as discarded concrete and bricks, is subjected to successive crushing, grinding, and sieving processes to produce

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RA. The use of RA as a substitute for NA in concrete production is regarded as one of the most effective pathways for recycling CDW, offering substantial economic, social, and environmental benefits [2, 3]. RA can be classified based on its physical and mechanical properties, including water absorption, specific gravity, crushing value, impact value, and abrasion resistance. Piccinali et al. [4] emphasized that the water absorption of RA is a critical parameter for assessing aggregate quality and must be considered in the mix design of concrete incorporating RA. The review reported minimum, average, and maximum RA water absorption values of 2.70%, 5.13%, and 14.70%, respectively. While high-quality RA demonstrates physical and mechanical properties similar to NA, the use of low-quality RA may significantly compromise the mechanical performance of recycled aggregate concrete (RAC) [5]. Dilbas et al. [6] found that the compressive strength of RAC was reduced by 36.37% and 2.3% relative to NAC for low-quality and high-quality RAs, respectively. Similarly, RAC exhibits reductions in modulus of elasticity of about 25% and 10% for low- and high-quality RA, respectively, relative to NAC [7–9]. RAC exhibits higher porosity due to the presence of adhered mortar and old interfacial transition zones (ITZ) in recycled concrete aggregates (RCA). This increased porosity enhances CO_2 diffusion, leading to greater carbonation depth. Compared with NAC, RAC shows an increase in carbonation depth of approximately 24% and 26% after 28 and 90 days of exposure, respectively [10]. This study investigates the effects of RA at different replacement levels on the mechanical properties and carbonation behavior of RAC. The concrete mixtures were designed in accordance with ÖNORM B 4710-1 [11] to comply with exposure class XC1.

2 Materials and Methods

The cement used in this study was CEM II/B-M (S-LL) 42.5 N, with a density of 3.05 g/cm^3. AHWZ Flumix, an Austrian supplementary cementitious material (SCM) composed of ground granulated blast-furnace slag (GGBS), fly ash, and limestone, was also used and had a density of 2.71 g/cm^3. A commercially available superplasticizer with a density of 1.05 g/cm^3 was employed as a chemical admixture. NA and RA, both with particle sizes of 0–16 mm, were sourced from a recycling plant in Austria. The RA used in this study was classified as RH-B, corresponding to processed RA derived from building construction and demolition waste, with a maximum brick content of 30% by mass, in accordance with ÖNORM B 3140 [12]. The physical properties of both aggregates were thoroughly characterized following ÖNORM EN 1097-6 [13], as summarized in Table 1.

RA was used to produce RAC with replacement levels of 0%, 25%, and 65%, while maintaining a constant water-to-binder ratio (w/b) of 0.69. The SCM was incorporated at 10% of the total binder content. The dosage of superplasticizer was adjusted to achieve a consistent initial workability of approximately 50 cm and was around 0.8% of the binder by mass. To ensure a consistent effective w/b, the RAs were pre-wetted to 80% of their water absorption capacity prior to casting. The detailed mixture proportions are presented in Table 2.

Concrete mixing was carried out by first dry-mixing the aggregates for 1 min. Subsequently, two-thirds of the mixing water was added, and mixing continued for 2 min.

Table 1. Physical properties of NA and RAs used in this study

Type of Aggregate	Fraction Size (mm)	OD particle density (g/cm^3)	SSD particle density (g/cm^3)	Water Absorption (%)
NA	0–16	2.65	2.72	2.7
RA	0–16	2.25	2.43	8.23

Notation: OD—oven-dried, SSD—saturated surface dry

Table 2. Mixture proportions of concrete mixes (kg/m^3)

Mixture	RA	W	B	C	SCM	W/B	NA	RA
XC1-0	0%	182	265	239	26.5	0.69	1880	0
XC1-25	25%	182	265	239	26.5	0.69	1410	398
XC1-65	65%	182	265	239	26.5	0.69	648	1021

Notation: W—water, B—binder, C—cement

Finally, the binder, the remaining one-third of the mixing water, and the superplasticizer were introduced, followed by an additional 3 min of mixing. The fresh concrete properties, including density and workability, were evaluated using EN 12350-6 [14] and EN 12350-5 [15], respectively. After casting, the specimens were demolded after 24 h and cured in a water tank for 28 days. Hardened concrete properties were assessed in terms of compressive strength (EN 12390-3) [16], modulus of elasticity (EN 12390-13) [17], and carbonation resistance (EN 12390-12) [18]. Cube specimens with dimensions of 150 mm were used for compressive strength test, while prism specimens 100 × 100 × 400 mm were used for modulus of elasticity and carbonation tests.

3 Results and Discussion

3.1 Fresh Density

Figure 1 presents the fresh density of concrete mixtures incorporating RA at replacement levels of 0%, 25%, and 65%. The measured fresh densities were 2359 kg/m^3 for the reference mix (XC1-0), 2322 kg/m^3 for the 25% RA mix (XC1-25), and 2249 kg/m^3 for the 65% RA mix (XC1-65). A clear decreasing trend in fresh density is observed with increasing RA content. The reduction in fresh density can primarily be attributed to the lower particle density and higher porosity of RAs compared to NAs [4]. RAs typically contain adhered mortar and old ITZs, which increase internal voids and reduce bulk density [19]. As the proportion of RA increases, these characteristics become more influential, resulting in a systematic reduction in the fresh density of RAC. The relatively small reduction observed at 25% replacement suggests that partial substitution of NA can be achieved without significantly altering concrete density, whereas higher replacement levels lead to more pronounced effects.

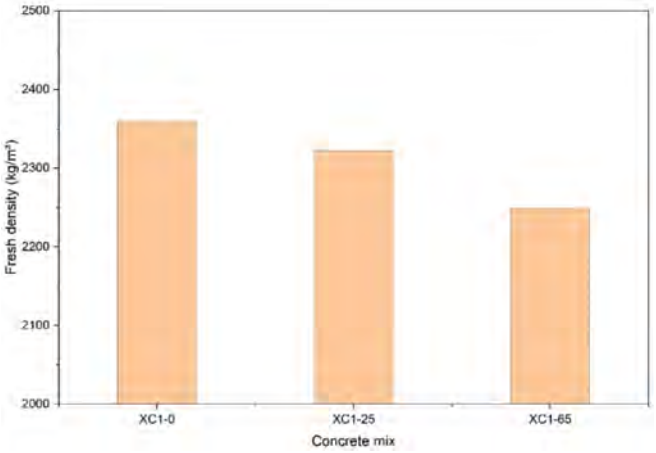


Fig. 1. Fresh density of concrete mixes

3.2 Compressive Strength

Figure 2 illustrates the compressive strength development of the concrete mixtures at 7 and 28 days. The reference concrete (XC1-0) exhibited compressive strengths of approximately 32 MPa and 42 MPa at 7 and 28 days, respectively. Incorporation of RA resulted in a systematic reduction in compressive strength at both curing ages. At 25% RA replacement (XC1-25), compressive strength decreased to about 29 MPa at 7 days and 40 MPa at 28 days, corresponding to relative reductions of 11.2% and 6.1%, respectively. A more pronounced reduction was observed for the 65% RA mixture (XC1-65), which showed compressive strengths of approximately 27 MPa and 37 MPa at 7 and 28 days, representing reductions of 17.8% and 12.4%, respectively. The observed strength reduction with increasing RA content is primarily attributed to the inferior mechanical properties of RA compared to NAs. RAs typically contain adhered old mortar and pre-existing microcracks, which weaken the aggregate particles and the new ITZ [20].

3.3 Modulus of Elasticity

The modulus of elasticity of the concrete mixtures is presented in Fig. 3. The reference concrete (XC1-0) exhibited a modulus of elasticity of 34.3 GPa. With the incorporation of RA, a gradual reduction in elastic modulus was observed. The modulus of elasticity decreased to 32.5 GPa for the 25% RA mixture (XC1-25) and further to 31.8 GPa for the 65% RA mixture (XC1-65), corresponding to reductions of approximately 5.2% and 7.3%, respectively, compared to the control mix. The reduction in modulus of elasticity with increasing RA content can be attributed to the lower stiffness of RA relative to NAs [21]. The presence of adhered mortar and microcracks within RAs leads to higher deformability and reduced elastic response under loading. In addition, the weaker and more heterogeneous ITZ between the RA and the new cement paste further contributes to the decrease in stiffness [22].

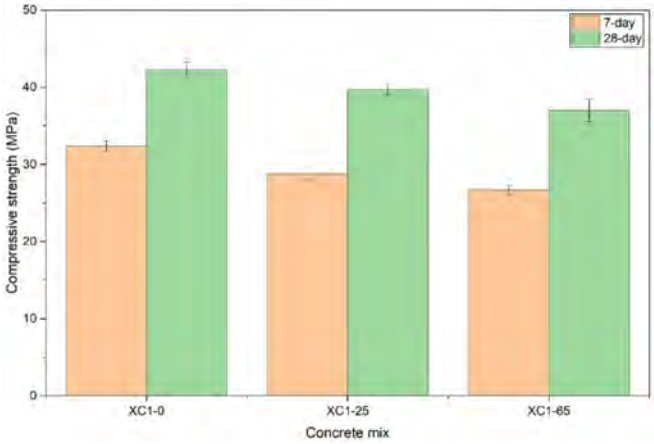


Fig. 2. Compressive strength at 7 and 28 days

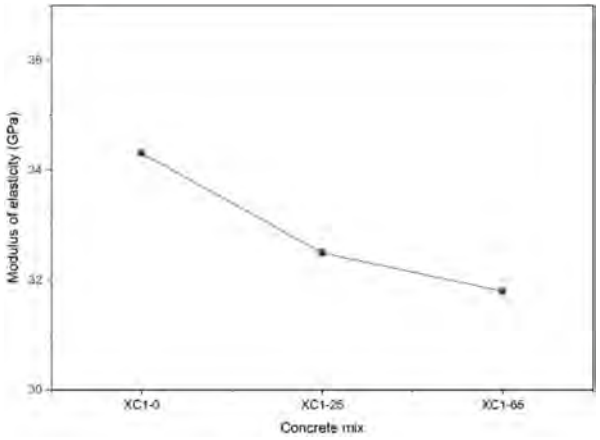


Fig. 3. Modulus of elasticity of concrete mixes

3.4 Carbonation Resistance

The evolution of carbonation depth is presented in Fig. 4. For the reference mixture XC1-0, the average carbonation depth increased from 1.0 mm at 0 days to 3.6 mm at 7 days, 7.7 mm at 28 days, and 12.5 mm at 70 days. The incorporation of RA led to deeper carbonation at all exposure ages. For mixture XC1-25, carbonation depths of 0.3 mm, 4.1 mm, 9.1 mm, and 15.0 mm were measured at 0, 7, 28, and 70 days, respectively. A further increase was observed for mixture XC1-65, which exhibited carbonation depths of 0.3 mm at 0 days, 4.2 mm at 7 days, 10.0 mm at 28 days, and 16.0 mm at 70 days. The increase in carbonation depth with higher RA content can be attributed to the more porous microstructure of RAC. RAs contain adhered old mortar and residual ITZs, which

increase overall porosity and facilitate CO_2 diffusion into the concrete matrix [23]. As a result, carbonation penetrates more rapidly in RAC than in NAC [24].

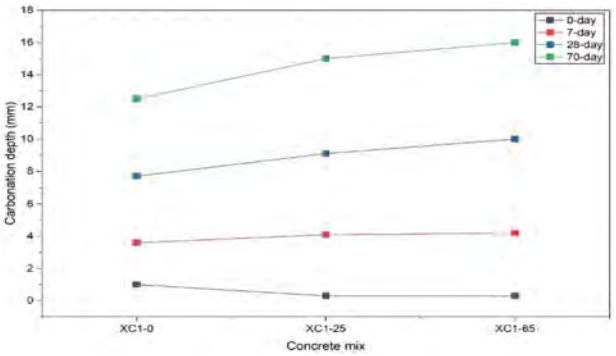


Fig. 4. Carbonation depth of concrete mixes over time

4 Conclusions

Concrete mixtures containing 0%, 25%, and 65% RA were assessed for fresh density, compressive strength, modulus of elasticity, and carbonation behavior. The results showed that increasing RA content reduced fresh density, compressive strength, and modulus of elasticity due to the higher porosity and lower density and stiffness of RA. Carbonation depth increased with both exposure time and RA replacement level, indicating enhanced CO_2 diffusion in the more porous microstructure of RAC. Overall, RAC with moderate RA replacement maintained acceptable mechanical performance, whereas higher replacement levels resulted in more significant reductions in strength and durability-related properties.

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Environmental Analysis of Petroleum Drill Cuttings in Amazonia for the Circular Economy in Road Infrastructure

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Abstract. The growing concern about the management of gas and oil extraction waste has driven the development of advanced analytical techniques to assess its environmental impact. This study aimed to analyze petroleum drill cuttings for the circular economy in road infrastructure from an environmental perspective. Based on the sampled depths, a synthetic well residue was prepared by combining cuttings from three drilling phases and contaminating them with water-based drilling fluids to ensure a realistic waste composition. Also, a granular mixture for pavement sublayers was produced by blending drill cuttings with natural soil fractions at a 15% by weight ratio. The elements barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), lead (Pb), and zinc (Zn) were detected by leaching and solubilization tests on 32 cutting samples from petroleum drilling wells in Brazilian Amazonia, as well as the synthetic well residue and the granular mixture. The results showed that the drill cuttings were not classified as toxic or hazardous waste. Also, the granular mixture used for road pavement in Amazonia, incorporating drill cuttings, soil, sand, cement, and gravel, was classified as Class II – A (non-hazardous and non-inert). Then, this composite matrix reduced metal mobility through dilution and physicochemical stabilization mechanisms. Finally, the results indicate that the reuse of drill cuttings in road pavements has the potential to serve as a sustainable solution for protecting local fauna and flora and a technically viable alternative within the circular economy.

Keywords: Drill Cuttings · Road Pavements · Physical Encapsulation · Chemical Stabilization · Circular Economy

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1 Introduction

The expansion of oil and gas exploration in environmentally sensitive regions, such as the Brazilian Amazon, has intensified concerns about the management of petroleum drilling waste, particularly drill cuttings. These residues consist of fragmented rock materials coated with drilling fluids and may contain elevated concentrations of trace metals and other potentially hazardous constituents. Inadequate disposal practices may result in soil and groundwater contamination, posing risks to local ecosystems and communities [1, 2].

In parallel, the transition toward a circular economy has encouraged the valorization of industrial residues in civil engineering applications, especially in road infrastructure, where large material volumes are required [3]. The incorporation of alternative materials into pavement layers, such as subbase or base courses, has been investigated as a strategy to reduce landfill disposal, preserve natural aggregates, and mitigate environmental impacts [4, 5]. However, the environmental feasibility of such reuse depends fundamentally on the mobility of contaminants under field-relevant conditions.

Drill cuttings may contain metals such as barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), lead (Pb), and zinc (Zn), depending on geological formation and drilling fluid composition [6]. Although total elemental concentration provides an initial indication of contamination, environmental risk is more closely associated with leaching and solubilization behavior, which govern contaminant mobility in aqueous systems [7]. In tropical regions with high rainfall intensity, such as Amazonia, these processes become even more critical due to enhanced percolation and runoff dynamics.

From a geotechnical perspective, incorporating drill cuttings into granular pavement mixtures with soil, sand, cement, and gravel may alter contaminant mobility through physical encapsulation and chemical stabilization mechanisms. Encapsulation can reduce contact between contaminants and infiltrating water, whereas cementitious reactions may promote immobilization via precipitation or adsorption onto hydration products [8, 9]. Nevertheless, these mechanisms must be experimentally validated, particularly under conditions representative of local climate and soil characteristics.

Therefore, this study evaluates petroleum drill cuttings from wells in the Brazilian Amazonia, focusing on their environmental behavior in leaching and solubilization tests and on their potential incorporation into granular pavement mixtures within a circular economy framework. The objective is to contribute to a technically sound and environmentally responsible strategy for waste valorization in road infrastructure.

2 Materials and Methods

To achieve the objectives of this study, the methodological steps presented in Fig. 1 were followed. Thirty-two onshore petroleum drill cutting samples were collected from wells located in the Brazilian Amazon region. The samples were air-dried at room temperature, manually disaggregated, homogenized, and sieved (< 9.5 mm) to ensure a representative particle size distribution for environmental testing. To simulate field conditions, a synthetic well (SW) residue was prepared by combining drill cuttings from three

drilling phases and adding water-based drilling fluid. This procedure aimed to reproduce the chemical composition typically found in real drilling waste after operational contamination.

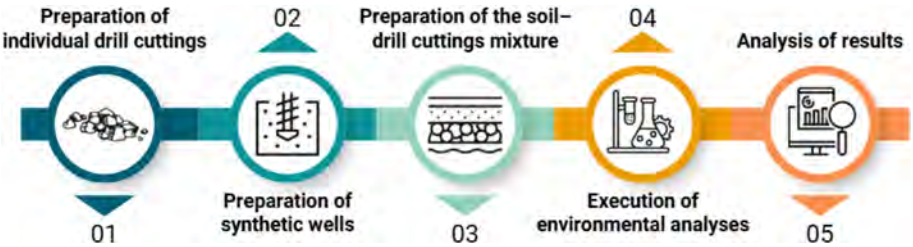


Fig. 1. Methodological steps.

After obtaining the SW material, a granular mixture (GM) was prepared to evaluate the influence of matrix incorporation on metal mobility when applied in pavement sublayers. The GM was produced by blending drill cuttings with natural soil fractions in predefined proportions (15% drill cuttings by weight relative to the matrix composition), followed by mechanical homogenization until a uniform distribution was achieved. All materials were conditioned at room temperature prior to environmental tests.

2.1 Preparation of the Synthetic Well

To simulate drill cuttings generated during the different phases of future drilling operations and to assess their potential for reincorporation into access road layers for drilling rigs, a synthetic well was designed. The well was defined based on drilling logs, characterization data from previously drilled wells, and regional geological maps. Drilling fluids were too prepared in the laboratory using the same formulations applied in the drilling operations of the reference wells, ensuring that the generated drill cuttings were representative of those expected in future drilling activities.

2.2 Preparation of Leaching and Solubilization Extracts

The leaching and solubilization tests were conducted to evaluate contaminant mobility in accordance with the classification criteria established by ABNT NBR 10004 [10]. The leaching procedure determines whether the waste exhibits hazardous characteristics (Class I), while the solubilization test differentiates between inert (Class II-B) and non-inert (Class II-A) non-hazardous materials.

For the leaching procedure, designed to simulate contaminant release under acidic percolation conditions similar to those occurring in landfill environments, representative solid samples were mixed with an acetic acid extraction solution adjusted to pH 4.93 $\pm$ 0.05, maintaining a liquid-to-solid ratio of 20:1 (L/kg). The suspensions were continuously agitated in a rotary extractor for 18 $\pm$ 2 h at room temperature. After extraction, the mixtures were filtered through 0.45 μm membrane filters, and the

leachates were preserved with nitric acid (pH < 2) in acid-cleaned polyethylene bottles until analysis.

The solubilization procedure was conducted to evaluate the potential release of contaminants under static contact with water, as required for determining inert or non-inert classification. Solid samples were mixed with deionized water at a liquid-to-solid ratio of 10:1 (L/kg) and maintained under controlled agitation for 5 h, followed by a 7-day static equilibrium period. After equilibration, the suspensions were filtered through 0.45 μm membranes.

2.3 ICP-OES Analysis and Data Treatment

The metal concentrations in the leaching and solubilization extracts were determined by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES, PerkinElmer Optima 8000). The instrument was operated under optimized conditions, including a radiofrequency power of 1.2 kW, plasma gas (argon) flow rate of 15 L min^{-1}, auxiliary gas flow rate of 0.2 L min^{-1}, and nebulizer gas flow rate of 0.8 L min^{-1}, with an axial viewing configuration to enhance sensitivity. The elements quantified were Ba, Cd, Cr, Cu, Fe, Mn, Pb, and Zn. Two emission wavelengths were initially monitored for each element. The most appropriate analytical line was selected based on signal stability, the absence of spectral interferences, and consistency relative to the calibration reference responses. Calibration was performed using multi-element standard solutions prepared from certified stock solutions covering the working concentration range of interest. The quality control procedures included reagent blanks, calibration verification standards, and replicate measurements to ensure analytical reliability. Negative concentration values were occasionally observed and interpreted as measurements below the instrumental limit of detection (LOD), due to background correction and signal fluctuations near the detection threshold. All analyses were conducted in triplicate, and the results were expressed in mg L^{-1}.

2.4 Classification of Residues and Mixtures

For data analysis and the classification of residues as hazardous or non-hazardous, inert or non-inert, the technical standard ABNT NBR 10004:2004 was adopted as the reference. However, this standard was recently updated in November 2024, revising certain classification procedures. The use of the 2004 version is justified by the transition period established for the implementation of the new standard, which determines that its mandatory application will only take effect from December 2026. Therefore, considering that the experimental procedures and the analysis of results were conducted during the validity period of the previous edition, the 2004 version was adopted as the normative reference for this study.

3 Results and Discussion

Pure drill-cutting samples, as well as the SW and the GM, were subjected to leaching and solubilization tests to enable toxicity classification in accordance with NBR 10004 [10]. Table 1 presents the results of the leaching test.

Table 1. Results of leaching extracts.

Sample	Concentrations of metals (mg L^{-1})							
	Ba	Cd	Cr	Cu	Fe	Mn	Pb	Zn
1	0.051	0.000	0.002	1.000	0.000	0.347	0.000	0.028
2	0.119	0.001	0.003	0.240	0.012	1.808	0.004	0.163
3	0.047	0.000	0.001	0.517	0.002	0.231	0.000	0.004
4	0.031	0.000	0.001	2.518	0.000	0.097	0.000	0.000
5	0.064	0.000	0.002	0.454	0.002	0.217	0.000	0.000
6	0.067	0.000	0.003	0.149	0.039	0.588	0.009	0.000
7	0.095	0.000	0.000	0.155	0.000	0.544	0.000	0.000
8	0.053	0.000	0.001	0.103	0.008	0.685	0.000	0.000
9	0.056	0.000	0.002	0.078	0.021	0.610	0.000	0.000
10	0.085	0.000	0.002	0.105	0.004	0.567	0.005	0.000
11	0.062	0.000	0.002	0.161	0.009	0.457	0.005	0.000
12	0.085	0.000	0.009	0.332	0.239	0.513	0.000	0.000
13	0.099	0.000	0.001	0.151	0.006	0.525	0.000	0.000
14	0.080	0.002	0.004	0.229	1.616	2.214	0.000	0.000
15	0.106	0.000	0.001	1.498	0.028	0.240	0.000	0.000
16	0.291	0.002	0.003	1.636	0.189	2.969	0.003	0.000
17	0.054	0.000	0.000	0.237	0.043	1.382	0.002	0.000
18	0.245	0.001	0.006	0.782	2.641	1.254	0.007	0.000
19	0.568	0.001	0.016	1.753	2.980	0.792	0.030	0.000
20	0.140	0.000	0.001	0.322	0.095	1.581	0.004	0.000
21	0.088	0.001	0.004	0.315	2.803	1.739	0.000	0.000
22	0.342	0.001	0.001	0.168	1.184	3.752	0.000	0.000
23	0.060	0.000	0.002	0.251	0.006	0.949	0.009	0.000
24	0.060	0.000	0.001	0.191	0.000	0.606	0.003	0.000
25	0.070	0.000	0.001	0.260	0.004	1.036	0.003	0.000
26	0.060	0.000	0.001	0.213	0.011	0.633	0.015	0.000
27	0.061	0.000	0.002	0.181	0.013	0.899	0.001	0.000
28	0.111	0.000	0.001	0.125	0.071	0.602	0.000	0.000
29	0.065	0.000	0.002	0.276	0.007	0.820	0.007	0.000
30	0.259	0.000	0.001	0.225	0.021	2.984	0.000	0.000
31	0.095	0.000	0.001	0.167	0.004	1.327	0.127	0.000

(*continued*)

Table 1. (*continued*)

Sample	Concentrations of metals (mg L^{-1})							
	Ba	Cd	Cr	Cu	Fe	Mn	Pb	Zn
32	0.041	0.002	0.005	0.477	0.893	0.886	0.069	0.000
SW	0.194	0.001	0.011	0.073	1.280	1.070	0.159	0.046
GM	0.299	0.000	0.006	0.045	0.010	1.060	0.014	0.402
Limits	70.000	0.500	5.000	–	–	–	1.000	–

For the samples and metals investigated, none of the pure drill cuttings, the SW impregnated with drilling fluid, or the GM exhibited concentrations above the prescribed limits. These findings indicate that the residues generated during well drilling, when used as a partial replacement of aggregates in a mixture, were not classified as toxic, being categorized as Class II – Non-hazardous waste, as they do not demonstrate the potential to contaminate groundwater reservoirs, soils, or surface water bodies under the evaluated conditions. Table 2 presents the results of the solubilization extract tests required to complete the classification procedure.

The second stage of the classification determines whether the material is inert or non-inert, with non-inert materials defined as those that exhibit solubilization exceeding the established regulatory limits when subjected to static contact with water. The solubilization results (Table 2) revealed greater variability in metal mobility under static water contact. Among the 32 individual drill cutting samples, six exhibited concentrations above the established limits for at least one element. Specifically, sample 1 exceeded the Pb limit. Samples 7, 12, 14, and 30 exceeded the limit for Mn, and sample 19 exceeded the Fe limit. These exceedances indicate that a portion of the drill cuttings must be classified as Class II-A (non-hazardous, non-inert) due to solubility levels above regulatory thresholds. The SW sample exhibited the highest degree of non-inert behavior, presenting exceedances for Ba, Fe, Mn, and Pb. This behavior is attributed to the combined effect of natural geological contributions and the incorporation of water-based drilling fluids, which may introduce additional soluble constituents and modify the chemical equilibrium of the system.

However, the incorporation of drill cuttings from well-drilling operations is proposed as a partial replacement for aggregates in the GM, corresponding to 15% of the total composition by weight, with the remaining fractions consisting of soil, sand, gravel, and cement. This incorporation significantly altered the mobility profile of the evaluated elements. In comparison with the SW sample, most metal concentrations decreased, suggesting a combined effect of dilution and physicochemical stabilization within the composite matrix. However, the solubilization results indicate that Cr concentration in the GM slightly exceeded the regulatory threshold (0.094 mg L^{-1} vs. limit of 0.050 mg L^{-1}). Therefore, strictly according to ABNT NBR 10004 [10] criteria, the GM cannot be classified as inert (Class II-B) and should be categorized as Class II-A (non-hazardous and non-inert). Despite this classification, the overall reduction in the mobility of Ba, Fe,

Table 2. Results of solubilization extracts.

Sample	Concentrations of metals (mg L^{-1})							
	Ba	Cd	Cr	Cu	Fe	Mn	Pb	Zn
1	0.035	0.000	0.002	0.331	0.001	0.061	*0.012	0.023
2	0.033	0.000	0.001	0.215	0.004	0.094	0.000	0.022
3	0.042	0.000	0.000	0.243	0.014	0.079	0.002	0.029
4	0.041	0.000	0.002	0.208	0.004	0.048	0.000	0.040
5	0.043	0.000	0.001	0.164	0.000	0.037	0.000	0.027
6	0.036	0.000	0.001	0.196	0.018	0.065	0.000	0.027
7	0.039	0.000	0.000	0.185	0.000	*0.113	0.000	0.021
8	0.034	0.000	0.001	0.155	0.001	0.035	0.000	0.039
9	0.028	0.000	0.003	0.154	0.000	0.056	0.000	0.037
10	0.031	0.000	0.000	0.188	0.004	0.039	0.000	0.020
11	0.033	0.000	0.000	0.254	0.007	0.059	0.000	0.024
12	0.041	0.000	0.010	0.334	0.096	*0.105	0.000	0.047
13	0.038	0.000	0.001	0.171	0.001	0.069	0.000	0.031
14	0.055	0.000	0.001	0.224	0.072	*0.966	0.000	0.050
15	0.054	0.000	0.002	0.726	0.004	0.078	0.008	0.051
16	0.392	0.000	0.003	0.777	0.031	0.097	*0.015	0.168
17	0.029	0.000	0.000	0.326	0.004	0.066	0.000	0.020
18	0.064	0.000	0.002	0.343	0.053	0.071	0.003	0.015
19	0.276	0.000	0.008	0.916	*1.772	0.023	0.010	0.069
20	0.040	0.000	0.001	0.267	0.002	0.043	0.000	0.024
21	0.043	0.000	0.001	0.276	0.007	0.089	0.000	0.043
22	0.059	0.000	0.002	0.287	0.090	0.063	0.000	0.041
23	0.047	0.000	0.001	0.462	0.013	0.096	0.000	0.024
24	0.046	0.000	0.001	0.317	0.002	0.037	0.000	0.022
25	0.045	0.000	0.002	0.225	0.000	0.093	0.000	0.038
26	0.044	0.000	0.001	0.281	0.000	0.076	0.002	0.028
27	0.039	0.000	0.001	0.298	0.005	0.098	0.000	0.033
28	0.044	0.000	0.002	0.104	0.002	0.071	0.000	0.058
29	0.045	0.000	0.001	0.118	0.001	0.065	0.002	0.035
30	0.052	0.000	0.000	0.104	0.000	*0.383	0.000	0.016
31	0.057	0.000	0.002	0.163	0.000	0.083	0.001	0.040

(*continued*)

Table 2. (*continued*)

Sample	Concentrations of metals (mg L^{-1})							
	Ba	Cd	Cr	Cu	Fe	Mn	Pb	Zn
32	0.047	0.000	0.001	0.200	0.005	0.063	0.000	0.032
SW	*0.716	0.000	0.008	0.096	*2.536	*0.192	*0.028	0.066
GM	0.094	0.000	*0.094	0.063	0.074	0.004	0.006	0.003
Limits	0.700	0.005	0.050	2.000	0.300	0.100	0.010	5.000

*Values above the established limit.

Mn, and Pb in the GM relative to the SW sample suggests that matrix incorporation contributes to partial immobilization mechanisms. These mechanisms may include physical encapsulation within the granular structure, adsorption onto soil and cement hydration products, and precipitation reactions promoted by alkaline conditions.

Further long-term leaching tests under dynamic conditions would be necessary to confirm the stability of these immobilization effects under field-relevant scenarios, particularly considering the high rainfall intensity typical of the Amazon region. Thereby minimizing environmental impacts associated with transport and final disposal. From a circular economy perspective, incorporating drill cuttings into pavement sublayers is a potentially viable alternative to landfill disposal, particularly in remote Amazonian regions where river-based logistics are required to transport waste to sanitary landfills. The partial reduction in metal mobility observed after matrix incorporation suggests that controlled reuse could help minimize environmental impacts while reducing demand for natural aggregate extraction.

4 Conclusion

Based on the results, the drill cuttings derived from petroleum well drilling, even after impregnation with drilling fluids and subsequent leaching and solubilization tests, did not exhibit contaminant concentrations exceeding regulatory thresholds for classification as toxic or hazardous waste. When incorporated into the GM at a proportion of 15% by weight, the materials were classified as Class II – A, that is, non-hazardous and non-inert. This classification indicates that incorporation into the composite matrix significantly reduces metal mobility through dilution and physicochemical stabilization mechanisms, thereby ensuring the environmental feasibility of their application in pavement sublayers.

Additional studies conducted by the research group, supported by laboratory mechanical characterization, have also demonstrated the technical feasibility of mixtures containing 15% drill cuttings for use in pavement base layers of oilfield access roads. This approach promotes the valorization of industrial by-products, reduces the demand for natural aggregate extraction, and mitigates logistical impacts associated with transportation and final disposal, particularly in environmentally sensitive forest regions. The findings demonstrate that the reintegration of these residues into road infrastructure represents a technically sound and environmentally safe alternative, consistent with circular economy principles.

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Mechanical Analysis of Petroleum Drill Cuttings Stabilized Layers for Sustainable Pavement Construction and Circular Economy in Amazonia

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Abstract. Drill cuttings are among the largest volumes of waste generated by gas and oil extraction activities. Given the growing demand for sustainable solutions in engineering and for alternative materials in infrastructure work, petroleum drill cuttings offer a promising alternative for more sustainable onshore disposals. This study evaluated the potential reuse of drill cuttings in soil-cement base and sub-base layers for industrial roads in remote production sites with low bearing soils and high logistical costs. Physical characterization tests were performed on 32 cuttings samples collected from drilling wells in Brazilian Amazonia. Based on the sampled depths, a synthetic well residue was prepared by combining cuttings from three drilling phases and subsequently contaminating them with the corresponding water-based drilling fluids to ensure a realistic waste mixture. Four mixtures were proposed by optimizing the proportions of drill cuttings and local low-bearing clayey soil over coarse and fine sand, cement and #1 crushed stone. For each mixture, compaction tests (Proctor), California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) tests were performed at 7- and 28-days curing. The mixture with 26.5% soil, 30% coarse sand, 26.5% #1 crushed stone, 2% cement, and 15% drill cuttings exhibited satisfactory performance as a pavement base layer, demonstrating the feasibility of reusing drill cuttings in oilfield road construction while reducing the demand for imported aggregate. Preliminary environmental results suggest reduced environmental impacts on local flora and fauna through sustainable waste management practices compared to disposal pits and landfills, in line with global circular-economy guidelines.

Keywords: Onshore Drilling Waste · Circular Construction · Drilling Muds · Stabilization/Solidification · Aggregate Blending Optimization

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1 Introduction

Increasing environmental concerns and the depletion of natural deposits have fostered a growing demand for research on sustainable solutions and alternative materials in infrastructure projects. The management and disposal of drill cuttings, solid wastes generated in oil and gas drilling activities, constitute an environmental concern due to their high volume and potential toxicity. One potential solution is the incorporation of drill cuttings as aggregate in pavement layers, contributing to the efficient design of oilfield road pavements and sustainable waste management practices.

The conventional drilling process for oil or gas wells is carried out using rotary drill bits that penetrate multiple rock layers, producing a large quantity of rock and soil fragments. Those are brought to the surface by introducing drilling fluids, whose thixotropic consistency allows pumping and avoids the settlement of a cuttings bed in the wellbore during the non-drilling time. Petroleum drill cuttings consist mainly of rock fragments impregnated with the drilling fluid base (either water, oil, synthetic fluids or gases), oil compounds, clays and chemical additives. Drill cuttings present an inherently variability in composition [1]. Their technical reuse in road construction depends on rigorous physicochemical and environmental characterization to ensure both mechanical stability and environmental safety [2].

An alternative for improving the mechanical performance and mitigating the environmental impacts of drill cuttings is solidification, defined as the encapsulation of drill cuttings within an impermeable solid matrix of high structural integrity [3]. Through solidification, drill cuttings may be reused in various applications. A cost-effective option is their use in pavement construction, such as in asphalt surface mixtures [4–6] or in treated granular pavement layers [4, 7, 8].

Tuncan et al. [9] evaluated the use of petroleum-contaminated drilling wastes as subbase material for road construction, applying stabilization/solidification techniques with lime, fly ash, and cement. The residues were predominantly fine-grained and potentially contaminated with oil and heavy metals. The mixture containing 20% lime, 10% fly ash, and 5% cement exhibited the best performance, achieving a California Bearing Ratio (CBR) of 44.5%, low permeability, and stability after freeze–thaw cycles. In addition to mechanical improvement, significant reductions in oil content and metal leaching were observed, indicating the formation of a dense matrix capable of immobilizing contaminants.

Similarly, Cordeiro [10] and Silva, Santos, and Lucena [11] investigated the stabilization of drilling wastes and oily residues with lime and cement for application in pavement layers. The materials, initially considered unsuitable and potentially hazardous due to the presence of fines, oil, and heavy metals, showed substantial improvements in mechanical properties after treatment, with CBR values meeting sub-base requirements. Environmental analyses indicated reduced hazardousness and effective immobilization of contaminants, demonstrating that stabilization can transform these wastes into technically feasible and environmentally safer materials for pavement applications.

In this context, this study evaluates the technical feasibility of reusing petroleum drill cuttings in soil–cement pavement layers using residues obtained from wells drilled in the Brazilian Amazon. Within this region, the limited availability of crushed stone and other natural aggregates, combined with high logistical costs and low-bearing soils, presents

construction challenges. To this end, physical characterization tests were performed, a representative synthetic well residue was developed, and different mixture compositions were designed and subjected to mechanical testing at various curing ages. This study seeks to contribute to sustainable waste management practices, aligned with circular economy principles, by reducing the environmental impacts associated with conventional disposal methods and the dependence on transported natural aggregates for oilfield road construction in remote production areas.

2 Materials and Methods

Thirty-two petroleum drill cutting samples previously collected from an oil basin in the state of Amazonas, northern Brazil, were investigated. These samples originated from 15 wells at varying drilling depths, grouped into three drilling phases according to the water-based drilling fluid composition used in the wellbore sections. Each sample was individually characterized by grain size analysis [12] and consistency-limits tests [13, 14] to enable classification according to the American Association of State Highway and Transportation Officials (AASHTO) system. The samples were classified into six distinct groups based on similarities in their grain size distribution and corresponding AASHTO classifications.

Since the available samples did not represent complete wells, as they were collected from different depths and locations, a representative synthetic well composition was defined to simulate a typical well in the investigated area. The sample selection criteria were based on geotechnical characterization, stratigraphy and lithology, drilling-fluid chemical composition, and the volumetric representativeness of the materials, considering sampled volumes and drill bit diameters. For each drilling phase, the selected samples were mixed in volume-weighted proportions and homogenized with the corresponding drilling fluid to reproduce contamination conditions (Fig. 1). According to these criteria, the representative well residue produced for this research consisted of 35.5% cuttings from phase 1, 37.87% from phase 2, and 26.64% from phase 3.

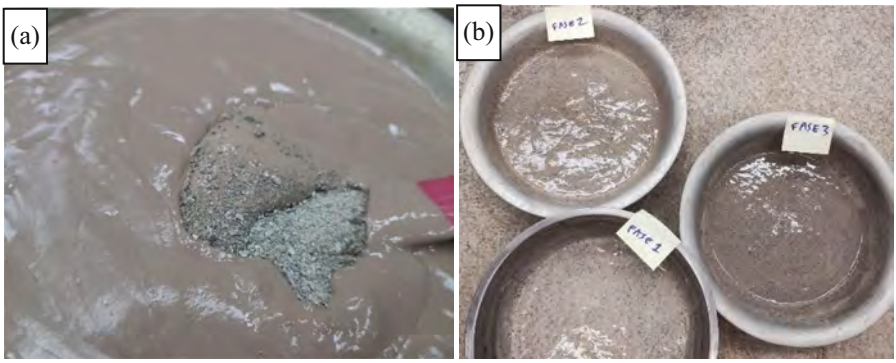


Fig. 1. (a) Mixing of phase 2 cuttings with the corresponding drilling fluid; (b) resulting muds from each drilling phase to be dried and mixed into synthetic drill cuttings material.

In the investigated oil basin region, reference mix designs are commonly employed for the construction of stabilized base and/or sub-base layers, consisting of local soil (collected from the same region as the synthetic well cuttings), sand, #1 crushed stone, and Portland Cement (ABNT CP II F-32). The local soil exhibits a low bearing strength and a high fines content, requiring soil-cement stabilization and crushed stone for its use in subbase and base layers, respectively. However, due to limited material deposits and high logistical costs in the region, the available compositions were found not to fully comply with the gradation ranges specified by the standards of the Brazilian National Department of Transport Infrastructure (DNIT). They also presented potential for technical and economic optimization. Therefore, new stabilized mixtures were proposed to achieve improved gradation compliance and enhanced mechanical performance for pavement applications.

Four experimental mixtures were developed. Mixtures A, B, and C consisted of local soil, coarse sand, and cement blend, with varying proportions aimed at optimizing the gradation and performance. Mixture D incorporated, in addition to the conventional materials, 15% drill cuttings from the synthetic well, partially replacing natural aggregates to evaluate the technical feasibility of their use in pavement layers. Due to the limited availability of drill cuttings in the region and the inability to obtain additional volumes, only one mixture containing this residue was proposed. The proportions of the proposed mixtures, as well as the reference mix designs, are presented in Table 1.

Table 1. Composition of the Studied Mixtures

Mixtures	Composition
Mixture A	60% Local Soil +38% Coarse Sand +2% Cement
Mixture B	60% Local Soil +37% Coarse Sand +3% Cement
Mixture C	60% Local Soil +35% Coarse Sand +5% Cement
Mixture D	26.5% Local Soil +30% Coarse Sand +26.5% #1 Crushed Stone +2% Cement + 15% Drill Cuttings from the Synthetic Well

For the proposed mixtures, compaction test with parameters of optimal moisture content (OMC) and maximum dry density (MDD) [15], CBR test with expansion evaluation [16], and Unconfined Compressive Strength (UCS) tests, in accordance with Brazilian National Department of Highways (DNER) [17], were performed. Tests on Mixtures A, B, and C were conducted using intermediate compaction energy, considering their predominantly sandy composition, absence of coarse aggregate, and intended application in pavement layers subjected to lower structural demand (sub-base layers). For Mixture D, the tests were carried out using modified compaction energy due to the presence of crushed stone and its proposed use in base layers, which require higher mechanical performance. Mechanical tests were performed at 7 and 28 days of curing to evaluate strength development over time and the influence of the cementation process on the mechanical behavior of the mixtures.

3 Results and Discussion

The physical characterization results (Table 2) of the 32 petroleum drill cuttings samples, based on grain size distribution and consistency limits, were used to organize the materials into six groups with comparable geotechnical behavior. The results indicate considerable variability in fines content, ranging from approximately 6% to over 50%. Sand was the predominant size fraction in most samples, whereas gravel was generally present in minor proportions, except in a few coarser materials. Plasticity limits (PL) were predominantly low, with most samples exhibiting non-plastic behavior or very low PL values, reflecting limited clay activity. Overall, the drill cuttings exhibit a heterogeneous yet predominantly granular and low-plasticity composition.

Table 2. Physical characterization of drill cuttings

Group	Samples	AASHTO	Description
I	4, 16	A-4	Sandy material with moderate to high fines content (37–51%) and low plasticity (PL $\leq$ 3).
II	1, 2, 5, 6	A-4	Moderately sandy material with high fines content (36–45%), non-plastic to slightly plastic (PL $\leq$ 3).
III	3, 14, 18, 19, 22	A-2-4	Predominantly sandy material with low fines content (12–19%) and non-plastic behavior.
IV	7, 11–13, 15, 20, 21, 23–25, 29	A-2-4	Sandy material with moderate fines (21–32%) and minor gravel fraction, predominantly non-plastic.
V	8, 17, 26, 27, 30–32	A-1-b	Well-graded sandy material with low fines (6–23%) and small gravel content, non-plastic behavior.
VI	9, 10, 28	A-1-b	Gravelly-sandy material with significant coarse fraction (38–47% gravel) and low to moderate fines (12–17%), predominantly non-plastic.

The results in Table 3 highlight the predominant role of gradation and compaction energy in controlling mechanical performance. Mixture D, which incorporated 15% petroleum drill cuttings and coarse aggregate, showed the most consistent strength development despite having one of the lowest cement contents. Its superior performance is primarily associated with the presence of crushed stone, which improved particle interlocking and load distribution, alongside the modified compaction energy, which enhanced densification. These results appear to indicate that gradation and compaction energy exerted greater influence than cement content alone, at least for the contents considered

in the research. Notably, the incorporation of drill cuttings did not impair performance, indicating that their use, from a mechanical standpoint, is technically feasible when combined with an optimized granular structure.

According to parallel environmental studies, at 15% cuttings content, Mixture D was also classified as non-hazardous and non-inert (Class II-A) in its unencapsulated (uncured) form based on leaching tests following the Brazilian solid waste classification standard [18]. This classification supports the use of cement stabilized pavement layers as a viable matrix for a solidification and encapsulation treatment for drill cuttings.

Table 3. Characterization of mixtures

Mixture	CBR (%)	Expansion (%)	UCS (MPa)	CBR (%)	Expansion (%)	UCS (MPa)	CBR (%)	Expansion (%)	UCS (MPa)
Curing time	Immediate evaluation			7 days of curing			28 days of curing		
A	19	0.00	*	–	–	–	–	–	–
B	80	0.00	*	21	0.10	*	24	0.23	*
C	87	0.10	*	–	–	–	–	–	–
D	106	0.24	*	104	0.33	0.69	127	0.00	1.02

Mixture	A	B	C	D	* Specimens disintegrated during soaking
OMC (%)	13,3	12,7	12,6	9,8	
MDD (g/cm³)	1,96	1,92	1,96	2,12	

Although Mixture A had a similar cement content to Mixture D, but without coarse aggregate, it showed the weakest mechanical performance, reinforcing the importance of an adequate granular structure. Mixtures B and C achieved satisfactory results; however, Mixture B is the more economical alternative due to its lower cement consumption. From a strictly empirical perspective, Mixture D stands out as the most suitable option for base layers owing to its coarse aggregate content and modified compaction energy. It presented the highest bearing capacity and was the only mixture capable of withstanding soaking, allowing the determination of UCS values. In contrast, Mixture B can be confidently adopted for subbase applications. The low expansion values observed in all mixtures constitute an additional advantage for pavement applications.

The particle size distribution curves of Mixtures B and D were compared with the gradation bands recommended by DNIT, as shown in Fig. 2. Neither mixture is perfectly contained within the specified envelopes. Nevertheless, both curves remain close to the recommended limits, without pronounced or systematic deviations. Mixture D exhibits a denser distribution in the intermediate and coarse fractions, contributing to improved particle interlocking and a more stable granular skeleton. Mixture B, although slightly finer, maintains a continuous gradation profile without noticeable gaps, which is also favorable for structural performance. Importantly, the minor departures from the DNIT gradation bands did not compromise mechanical behavior.

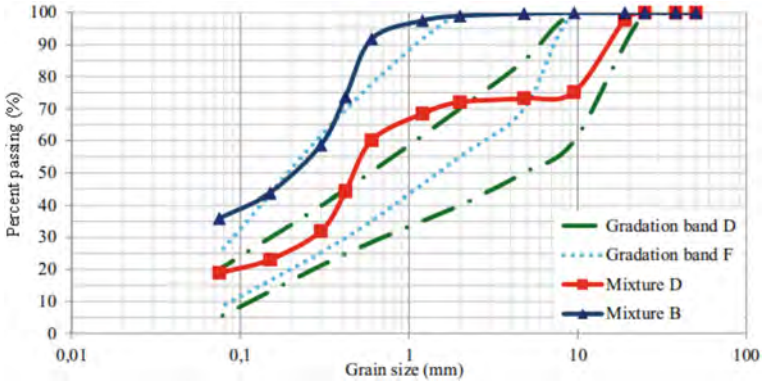


Fig. 2. Particle size distribution of Mixtures B and D compared with DNIT gradation bands.

4 Conclusions

This study demonstrates that petroleum drill cuttings can be viably reused as aggregate in pavement foundation, particularly when properly blended with locally sourced aggregates and compacted in cement-stabilized layers. All mixtures tested exhibited low expansion without impaired performance, indicating technical feasibility for oilfield-road pavements while improving the mechanical properties of the local low bearing soils. Laboratory testing based on CBR and UCS performance criteria of mixtures incorporating up to 15% drill cuttings showcased that adequate gradation, inclusion of coarse aggregate (crushed stone) and appropriate compaction energy exerted a stronger influence on bearing strength than cement content alone for base layers. Meanwhile, mixtures lacking crushed stone were shown to be suitable for subbase applications.

Beyond technical feasibility, reuse offers notable economic and environmental benefits. Drill cuttings helped stabilize a low-bearing, fines-rich soil into an aggregate blend that achieves the desired gradation with a reduced crushed stone content, thereby lowering the demand for natural aggregates and transport needs in oilfields with high logistical costs. Furthermore, incorporating drill cuttings into soil-cement pavement layers reduces the need for on-site disposal pits by enabling a solidification/encapsulation treatment within the pavement structure. At 15% cuttings content, the studied mixture was classified as non-hazardous and non-inert in its unencapsulated (uncured) state based on leaching tests. This strategy helps avoid site degradation and local environment impacts associated with conventional drilling waste management practices. Overall, the results support integrating petroleum drilling residues into oilfield road infrastructure as a sustainable, cost-effective strategy aligned with circular economy principles and responsible local resource management.

Acknowledgments. The authors acknowledge the financial support provided by Petrobras through the research project “Study on the use of residues from the Urucu petroleum province (Amazonas, Brazil) in civil infrastructure applications”, developed in cooperation with the Federal University of Ceará (UFC) and the Pavement Mechanics Laboratory (LMP).

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Carbon-Negative Renders: Integrating Hemp and Biochar for Circular Building Material

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Abstract. The transition towards a circular and regenerative built environment demands innovative building materials that combine low-carbon footprint, thermal efficiency, and resource circularity. This study explores the formulation and performance of a novel sustainable render based on a composite of hemp fibers and biochar, aimed at enhancing the environmental and functional performance of building envelopes. The composite render replaces a portion of conventional mineral binder and plastic fibers with bio-based and carbon-rich materials, thereby reducing embodied carbon and contributing to carbon sequestration. Laboratory testing evaluated the render's physical properties (density, porosity), mechanical properties and capillarity. Results indicate that adding biochar and/or hemp, reduces bulk compared to conventional renders, while the hemp fraction improves render flexibility making it especially suitable for retrofit, renovation, or low-rise construction in climates where moisture regulation and energy efficiency are critical. Beyond material performance, this render aligns with circular economy principles by valorizing agricultural by- products (hemp) and pyrogenic carbon (biochar), offering a viable pathway toward carbon-negative building envelopes. The study concludes that hemp– biochar renders represent a promising sustainable alternative for future building practices and recommends further long-term durability and indoor-climate studies to support broader adoption.

Keywords: Hemp fiber · biochar · sustainable render · circular building materials

1 Introduction

The integration of biochar and hemp into building materials represents a promising approach for developing carbon-negative renders, supporting circular economy principles in the construction sector. Biochar, a carbon-rich material produced through the thermochemical conversion of biomass residues under limited oxygen, is recognized for its negative CO_2 footprint and multifunctional properties, including high porosity, low thermal conductivity, and chemical stability. These characteristics make biochar an effective additive or partial replacement for cement and sand in construction materials, enabling both carbon sequestration and performance enhancement in building applications [1–4].

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Biochar's carbon-negative status arises from its ability to sequester atmospheric CO_2 through plant photosynthesis, generating carbon that is stored in a stable form for hundreds of years. When incorporated into construction materials, biochar not only reduces the carbon footprint of these products but also contributes to waste valorization and resource circularity by utilizing biomass residues that would otherwise be discarded [1, 5–7]. Studies have demonstrated that replacing a portion of cement or sand with biochar can result in significant reductions in CO_2 emissions, with some applications achieving up to −65 kg CO_2-eq per ton of material or a 40% reduction in the carbon footprint of concrete [7–9]. Furthermore, biochar's porous structure facilitates CO_2 diffusion, enhancing carbonation efficiency and depth in cement-based materials [9]. Combining biochar with natural fibers such as hemp further enhances the sustainability and performance of building materials. Hemp-based composites are valued for their eco-friendly nature, energy efficiency, and low pollutant emissions during production.

The use of biochar and hemp in building materials aligns with circular economy principles by promoting waste utilization, reducing reliance on non-renewable resources, and transforming buildings into long-term carbon sinks. This approach supports the development of low-carbon or carbon-negative construction materials, contributing to emissions reduction and sustainable development in the built environment [1, 3, 6, 7]. The adoption of these materials is further supported by their potential to improve energy efficiency, regulate humidity, and provide insulation in buildings, thereby offering both environmental and functional benefits [3, 10]. The integration of biochar and hemp into renders and other building materials offers a viable pathway towards carbon-negative, circular construction practices, with demonstrated benefits in carbon sequestration, material performance, and resource sustainability [1, 3, 9, 11].

2 Materials and Methods

2.1 Materials

The primary binder used was CEM II 32.5 Portland combined with 0–4 mm river silica sand as the aggregate at a 1:2 ratio by weight. The water-to-cement ratio was kept constant at 0.4 for all mixtures to ensure comparability, while a superplasticizer (Viskocrete-10, Sika) was used to maintain the desired workability of 11 ± 1 cm as per EN 1015-3.

The experimental materials investigated by this study were biochar as partial binder replacement and hemp fibers as reinforcing additives. The biochar used was fine- grained cyclone biochar with an average grain size of approximately 60 μm. Before integration in the mixture, the hemp fibers were manually cut to about 15 mm in length and chemically treated using a silane agent and coated with nano-silica to improve durability and reduce water absorption. Both the biochar's and the treated fibers' true density was determined via gas pycnometer (Ultrapyc 3000, Anton Paar, Austria) to be 2.16 g/cm3 and 1.86 g/cm3, respectively. Figure 1 presents the SEM image of how the fiber treatment was effective (a) and how both fibers and biochar were incorporated homogeneously into the mixture (b).

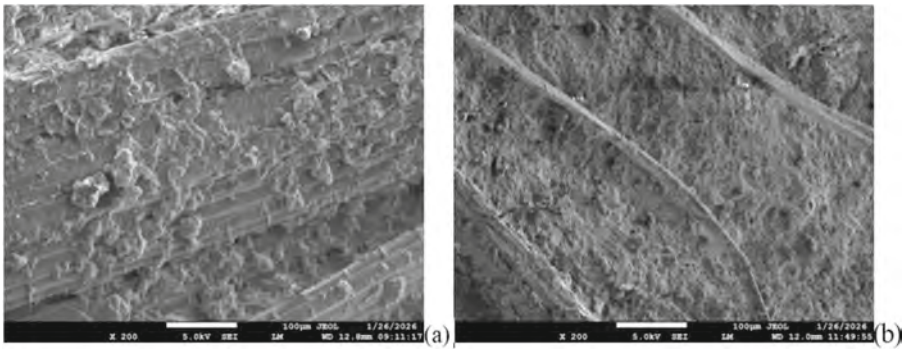


Fig. 1. SEM images of treated fiber (a) and mixture with fiber and biochar (b).

2.2 Mixture Design and Specimen Preparation

For the study, five experimental mixtures were produced: REF (reference mortar), HF (1.5% by volume treated hemp fibers), BC2.5% (2.5% biochar replacement), BC5% (5% biochar replacement), and BCF (2.5% biochar replacement +1.5% by volume treated hemp fibers). The exact compositions of the mixtures are presented in Table 1 below.

Table 1. The composition of the mixtures made for this study.

Mixture	Cement (g)	Biochar (g)	Silica Sand (g)	Water (g)	Treated Hemp Fibers (g)	Superplasticizer (g)
REF	3000	0	6000	1200	0	0
HF	3000	0	6000	1200	243.7	10
BC2.5%	2925	75	6000	1200	0	10
BC5%	2850	150	6000	1200	0	20
BCF	2925	75	5700	1200	243.7	20

The mortars were mixed using a large planetary mixer following a consistent mixing protocol. The fresh mixtures were then cast into 40 × 40 × 160 mm metal molds and subsequently mechanically compacted on a vibration table for 45 s to ensure uniformity and to avoid clumping of the experimental material. A total of 15 mortar prisms were prepared for each mixture.

After 24 h, specimens were demolded and transferred to a controlled curing chamber at 20 °C and 95% relative humidity until testing at 7, 28, and 90 days. On the 28-day mark, an additional 3 samples of each mixture were removed from the curing chamber, being inserted for 28 days into an accelerated carbonation chamber with 2.5% CO_2 concentration, 24 °C and 50% RH.

2.3 Tests Conducted

To assess the effects that the cyclone biochar and treated hemp fibers had on the mechanical strength, physical properties and carbonation of the produced mortars, an experimental test regimen was conducted. The tests, specimen ages, methodology and equipment used are summarized in Table 2.

Table 2. Summary of experiments and procedures used in the study.

Test	Specimen Age	Methodology	Equipment	Notes
Flexural Strength	7, 28, 90 days	EN 196-1	Proeti HR017 Universal Testing Machine	3-point bending
Compressive Strength	7, 28, 90 days	EN 196-1	Proeti HR017 Universal Testing Machine	Performed with fractured halves
Dynamic Modulus of Elasticity	7, 28, 90 days	EN 12504-4	Proceq Pundit lab +	
Porosity, absorption & specific gravity	7, 28, 90 days	RILEM CPC 11.3	Custom void chamber	

3 Results and Discussion

3.1 Mechanical Properties

The progression of flexural strength, compressive strength and dynamic modulus of elasticity of all mixtures is presented in Figs. 2a, b and 3 respectively.

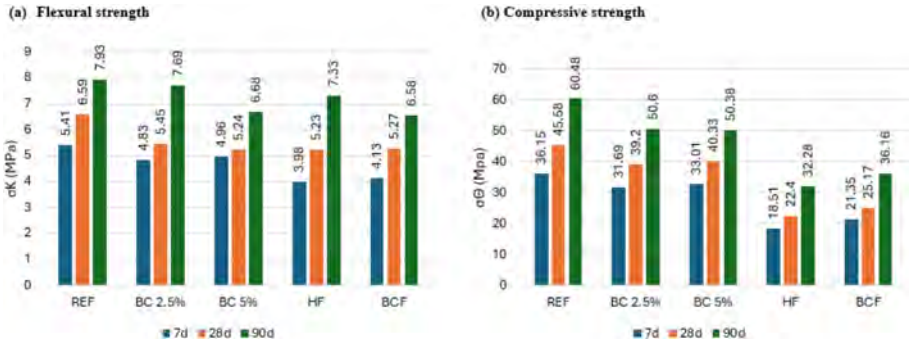


Fig. 2. Flexural (a) and compressive (b) strength of the mixtures at ages of 7, 28 and 90 days.

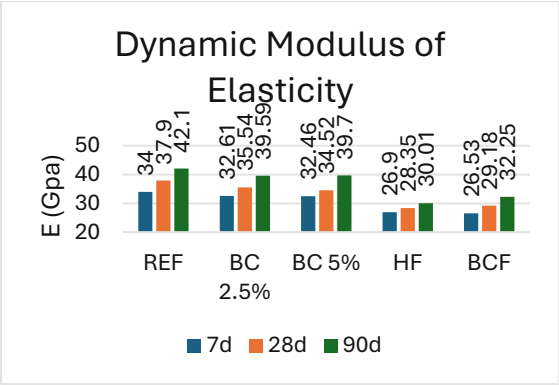


Fig. 3. Dynamic Modulus of elasticity of the mixtures at ages of 7, 28 and 90 days

Biochar incorporation has led to minor to moderate reductions in both mechanical strengths and the dynamic modulus of elasticity at all ages when compared with the reference mixture. At 90 days, both the BC 2.5% and 5% samples had a compressive strength of about 50 MPa (~16% reduction from reference) and a modulus of elasticity of about 39.5 GPa (~6% reduction from reference). The flexural strength at 90 days also showed little deviation from the reference mixture, especially for the 2.5% mixture (only a 3% reduction). Notably, doubling the biochar content from 2.5% to 5% didn't result in significant deterioration of strength, indicating that an even greater amount of biochar could possibly be integrated without compromising the mechanical properties of the material.

In contrast, treated hemp fiber incorporation significantly impacted the mechanical properties of the mixtures. At 90 days, the HF samples reached approximately 32 MPa in compression (about 47% lower than REF), while the corresponding dynamic modulus was approximately 30 GPa (about 29% reduction), perhaps indicating increased porosity created by the addition of the fibers. The biochar–fiber mixture (BCF) demonstrated slightly higher mechanical performance, reaching approximately 36 MPa in compression and 32 GPa in dynamic modulus at 90 days, indicating that the biochar may counteract the matrix weakening associated with fibers. In terms of flexural behavior, the HF mixture achieved 7.73 MPa at 90 days, remaining comparable to the reference, while BCF showed a slightly lower value. Notably, all fiber-reinforced specimens did not fully separate after cracking but remained held together due to fiber bridging.

3.2 Physical Properties

The results for porosity, absorption and specific weight of the samples are presented in Figs. 4a, b and 5 respectively.

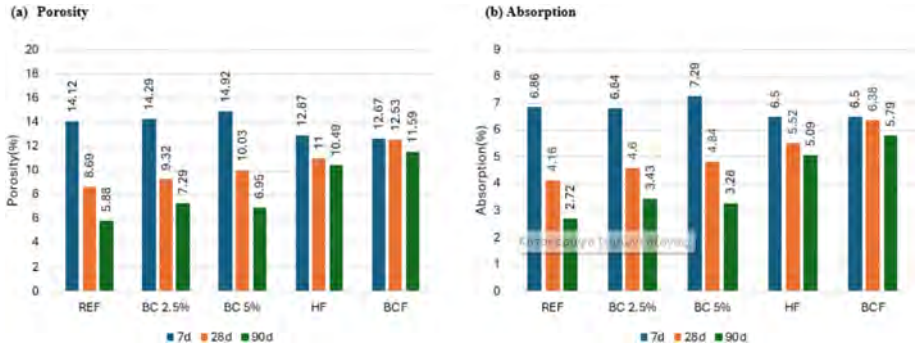


Fig. 4. Porosity (a) and absorption (b) of the mixtures at 7, 28 and 90 days.

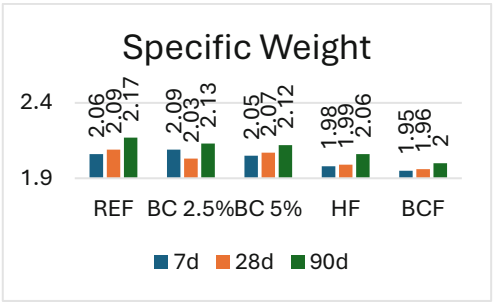


Fig. 5. Specific weight of the mixtures at 7, 28 and 90 days.

The addition of the biochar has led to a moderate increase in porosity (~20% for both mixtures at 90 days) when compared with the reference mixture. Consistent with the mechanical strength results, the 2.5% and 5% biochar mixtures showed similar progression for porosity and absorption and didn't deviate from each other, despite doubling the biochar content. Specific weight was slightly lower than the reference, due to the lower density of biochar when compared to cement.

Fiber integration in the mixtures led to a more drastic increase in porosity with the HF mixture having a 78% higher porosity than the reference and BCF a 97% higher porosity. Water absorption showed similar trends, while specific gravity was consistently lower (by about 6%) than the reference for both HF and BCF. These results, in conjunction with the mechanical strength and dynamic modulus of elasticity results, seem to corroborate that the introduction of fibers has a strong influence in the uniformity and compactness of the specimens.

3.3 Thermogravimetric Analysis

Figure 6 presents the thermogravimetry testing results.

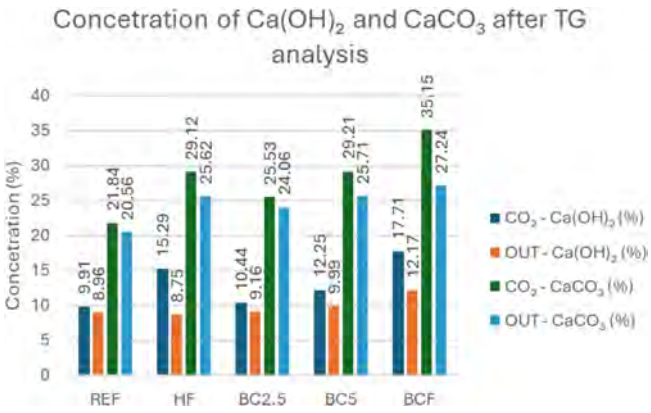


Fig. 6. Mass percentages obtained through thermogravimetry analysis

The total amount of $Ca(OH)_2$ and $CaCO_3$ was calculated by using the percentage loss obtained by the equipment analysis and the molecular weight of the components. The inclusion of biochar seems to have increased the carbonation of the samples, due to the calcific nature of biochar and the slight increase in porosity. Comparing the results between the samples, BCF presents the highest percentage of both molecules. HF also shows a high percentage of $Ca(OH)_2$. The existence of fibers influenced the open pores on the material, directly interfering with the CO_2 transportation inside the structure and, therefore, its carbonation. The higher percentage of $CaCO_3$ on BCF relates to both fibers and biochar present in the mixture, as can be insinuated when observing the values obtained for the other samples.

To observe long-term durability, possible application as insulation and the challenges related to the material, further examination is necessary, including the use of tests related to exposure of different environments. Only after that would it be possible to have a better understanding of the uses and applications that this study has shown so far.

4 Conclusion

This study evaluated the mechanical and physical behavior of CEM II 32.5 mortars incorporating cyclone biochar as partial binder replacement and chemically treated hemp fibers as reinforcement. Within the investigated range, biochar addition resulted in moderate reductions in compressive strength and stiffness ($\approx$16% and $\approx$6% at 90 days, respectively), accompanied by an approximately 20% increase in porosity, while showing limited sensitivity to dosage between 2.5% and 5%. Hemp fiber incorporation produced a more pronounced increase in porosity and corresponding reductions in compressive strength; however, flexural performance at later ages remained comparable to the reference mixture, and specimens retained structural integrity after cracking due to fiber bridging. The combined biochar–fiber specimens demonstrated partial regain of the compressive strength relative to the fiber-only mixture, indicating effects beyond total porosity. Overall, the findings show that biochar and natural fibers can be incorporated

in relatively large amounts into cement-based materials in a controlled manner without severely compromising mechanical performance, offering a practical pathway for incorporating bio-based and carbon-rich by-products into structural materials. Further research should be focused on counteracting the impact of the experimental materials on mechanical and physical properties, as well as determining the hygrothermal properties of the materials, for potential use as thermal insulation.

For those properties, in-depth data related to the microstructure of the material and its hygrothermal performance will need to be obtained, determining the possible applications of the mortars used in this study.

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Heavy-Aggregate Renders Incorporating Emery for High-Demand Construction Applications

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Abstract. The increasing demand for durable construction materials suitable for severe service conditions has renewed interest in the use of heavy aggregates in cement-based systems. This study investigates the incorporation of emery, a natural abrasive rock characterized by high density and hardness, in cementitious renders intended for protective applications. Three mortar mixtures were produced: a reference mixture (REF) and two modified mixtures incorporating emery aggregates (EA) and emery powder (EP). The incorporation of emery improved the mechanical performance of the mortars. At 90 days, the mixture containing emery powder exhibited an increase in flexural strength of approximately 22%, while compressive strength increased by about 13% compared with the reference mixture. The dynamic modulus of elasticity increased by up to 23%, while open porosity decreased by up to 18%. In addition, mortars containing emery showed improved resistance to impact loading and enhanced surface hardness. Overall, the results indicate that the incorporation of emery can significantly enhance the mechanical performance and durability of cement-based renders, highlighting their potential application in demanding construction environments.

Keywords: Heavy aggregates · emery · dense renders · high-temperature stability · sustainable materials · industrial by-products · special applications

1 Introduction

The cement and concrete sector have committed to significant reductions in greenhouse gas emissions in alignment with the European decarbonization strategy targeting climate neutrality by 2050. According to the Global Cement and Concrete Association (GCCA) [1], key strategies include reducing the CO_2 emission intensity of cement production and increasing the use of supplementary cementitious materials (SCMs), such as fly ash, slag, calcined clays, and natural pozzolans, in order to de-crease the clinker-to-cement ratio and promote the development of low-carbon construction materials.

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In this context, improving the durability and service life of construction materials is essential for reducing the environmental footprint of infrastructure. At the same time, the use of industrial by-products as SCMs has attracted increasing research interest. Conventional SCMs such as fly ash, slag, metakaolin, and calcined clays have been widely studied [2], while additional industrial residues and mineral by-products, including perlite processing residues [3] and porcelain waste [4], have also been investigated as potential components of cement-based materials.

Among alternative materials for cementitious composites, emery has attracted attention due to its high hardness (Mohs 8–9) and mineralogical composition. Natural emery is a granular metamorphic rock mainly composed of corundum (Al_2O_3) and iron oxides such as magnetite, which provide high hardness and abrasive properties. For this reason, emery is widely used in grinding, polishing, and surface treatment processes, as well as in specialized industrial applications such as wear-resistant flooring and rice milling.

Greece and Turkey constitute the main global suppliers of natural emery. In Greece, significant deposits are located on Naxos Island near the settlement of Apeiranthos, where extraction has been documented since antiquity and represents one of the largest natural emery resources in Europe [5]. Emery extracted from these deposits is processed and graded for export, mainly supplying European polishing industries and Asian rice milling sectors. Turkey also represents a major producer and exporter of natural emery, particularly through companies located in the Izmir region.

Although emery has rarely been investigated as a constituent of cement- or concrete-based materials, recent studies have explored its potential use in cementitious composites, particularly in high-performance concrete and restoration mortars [6–8]. In one study, emery aggregates were incorporated into a high-performance concrete mixture in which part of the cement was replaced by limestone filler and nano-silica was added to compensate for strength reduction and refine the microstructure [6]. In another investigation, an industrial self-compacting concrete mixture was modified by reducing the cement content and partially substituting the binder fraction with emery powder, achieving reduced CO_2 footprint while maintaining adequate mechanical performance [7]. Furthermore, mortars incorporating cement replacement levels of up to 50% with emery powder have been investigated, indicating potential applicability in restoration mortars [8].

Despite these studies, the use of emery as a heavy aggregate in cementitious renders has not been systematically investigated. Therefore, the present study aims to investigate the incorporation of emery aggregates and powder in cement-based renders and to evaluate their influence on density, mechanical performance, dimensional stability, and resistance to aggressive environmental conditions.

In addition, the high density and iron oxide content of emery may enhance radiation shielding performance. Materials containing heavy elements, such as iron-rich aggregates, have been shown to exhibit higher attenuation coefficients for γ- and X- rays compared with conventional aggregates such as limestone or silica sand. Previous studies indicate that replacing conventional aggregates with iron-rich materials can improve radiation attenuation by approximately 10–12% [9].

2 Materials and Methods

Three cement-based mortar mixtures (renders) were prepared in order to investigate the incorporation of emery in cementitious mortars. A reference mixture (REF) was produced, while two modified mixtures were developed incorporating emery aggregates (EA) and emery powder (EP). All mixtures were prepared according to the European standard for cement mortars (EN 196-1). The water-to-cement ratio (w/c) was kept constant at 0.40 and the cement content of the reference mixture was fixed at 3000 g. Natural siliceous sand (0–2 mm) was used as the reference aggregate. In the modified mixtures, emery was introduced as a partial volumetric replacement of conventional materials. In mixture EA, part of the natural sand was replaced on an equal-volume basis by emery aggregate fractions (R16 and R30), corresponding to approximately 18.3% of the total sand volume. In mixture EP, the same volumetric replacement of aggregates was applied, while an additional partial volumetric replacement of cement (≈2.7%) was carried out using emery powder.

The renders proportions are presented in Table 1. The measured consistency ranged between 12 and 13 mm for all mixtures (EN 1015-3: 1999).

Table 1. Composition of the mortar mixtures (renders).

Component (g)	REF	EA	EP
Cement	3000	3000	2919
w/c	0.4	0.4	0.4
Emery powder (2.7% v.v.)	–	–	99.8
Silicate sand (0–2 mm)	6000	4902	4902
Emery sand, R16 (9.0% v.v.)	–	782.5	782.5
Emery sand, R30 (9.3% v.v.)	–	810.7	810.7
Consistency (mm)	12.5	13	12

The mechanical and physical properties of the mortars were evaluated using standardized testing procedures. Flexural and compressive strength were determined according to EN 196-1, while the modulus of elasticity was measured following ASTM C597. Open porosity and specific gravity were evaluated according to RILEM CPC 11.3. Microstructural characterization was performed by SEM. Surface hardness was assessed using a Schmidt rebound hammer in accordance with ASTM C805, while impact resistance was evaluated through a drop-weight test based on EN 1339:2003/A2:2006. The radiation-shielding properties of the mortars were also investigated. The attenuation coefficient of the three mortar types was determined experimentally using a high-resolution spectroscopic system. A sealed Eu-152 radioactive source was employed due to its multi-energy photo-peaks, and photon attenuation was measured with a High Purity Germanium (HPGe) detector with 50% relative efficiency.

3 Results

3.1 Physico-Mechanical Properties

The physico-mechanical performance of the investigated mortars was evaluated through flexural strength, compressive strength and dynamic modulus of elasticity measurements at 28 and 90 days of curing (Fig. 1).

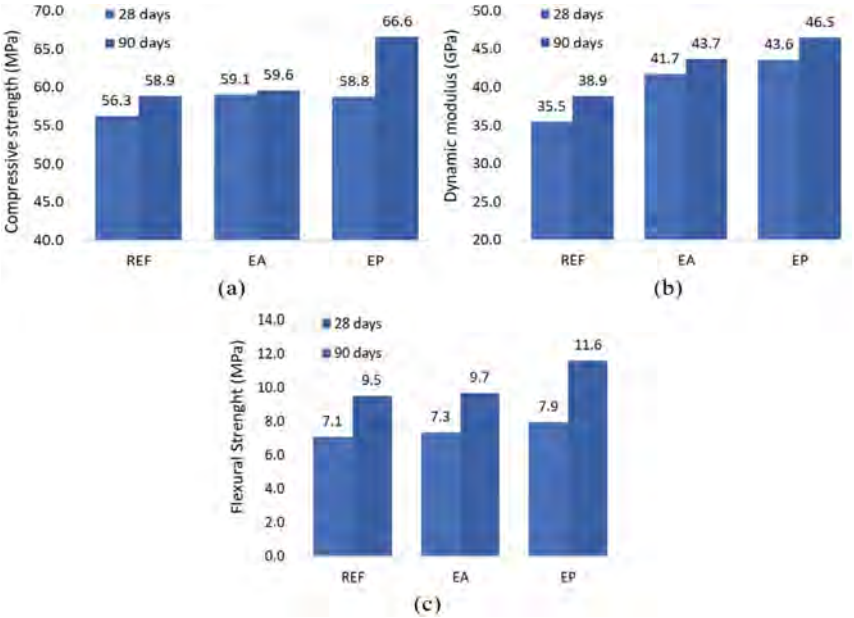


Fig. 1. Physico-mechanical properties of the investigated mortars: (a) compressive strength, (b) dynamic modulus of elasticity, and (c) flexural strength at 28 and 90 days.

The incorporation of emery resulted in improved flexural strength. At 28 days, the EP mixture reached 7.9 MPa compared with 7.1 MPa for the reference mixture (≈11% increase). At 90 days, flexural strength increased to 11.6 MPa for EP and 9.5 MPa for the reference mortar (≈22% increase). The EA mixture showed smaller improvements, reaching 7.3 MPa at 28 days and 9.7 MPa at 90 days (≈3–4% increase). A similar trend was observed for compressive strength. At 28 days, the EA mixture showed the highest value (59.1 MPa), corresponding to an increase of ≈5% compared with the reference mixture (56.3 MPa), while the EP mixture reached 58.8 MPa (≈4% increase). At 90 days, the EP mixture exhibited the highest compressive strength (66.6 MPa), representing an increase of ≈13% compared with the reference mixture (58.9 MPa).

The dynamic modulus of elasticity also increased in mortars containing emery. At 28 days, EA and EP reached 41.7 GPa and 43.6 GPa, respectively, compared with

35.5 GPa for the reference mortar (≈17% and 23% increase). After 90 days of curing, the dynamic modulus reached 43.7 GPa for EA and 46.5 GPa for EP, corresponding to increases of ≈12% and 20%, respectively, compared with the reference mixture (38.9 GPa).

The pore structure of the mortars was evaluated through open porosity measurements, while density characteristics were assessed through specific gravity at 28 and 90 days (Fig. 2). At 28 days, the reference mortar exhibited the highest open porosity (12.10%), whereas EA and EP showed lower values (9.92% and 10.06%), corresponding to reductions of ≈18% and ≈17%, respectively. After 90 days, porosity decreased for all mixtures, indicating progressive densification of the cementitious matrix. The EP mixture presented the lowest porosity (5.76%), about 12% lower than the reference mortar (6.55%), in agreement with [7], while EA showed a slightly higher value (7.09%).

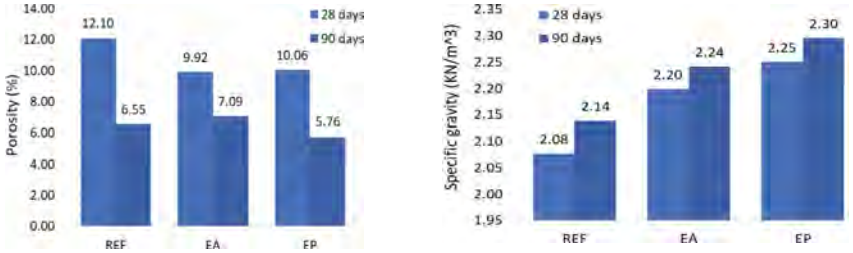


Fig. 2. Physical properties of the investigated mortars (a) open porosity, and (b) Specific gravity at 28 and 90 days.

The specific gravity results showed higher values for mortars containing emery. At 28 days, the reference mortar exhibited the lowest value (2.08), while EA and EP reached 2.20 and 2.25, respectively. A similar trend was observed at 90 days, with EP presenting the highest specific gravity (2.30), followed by EA (2.24) and REF (2.14), reflecting the higher density of emery particles.

3.2 Surface Hardness (Rebound Hammer Test)

The surface hardness of the investigated mortars was assessed using the Schmidt rebound hammer test. The results, expressed as rebound number (R), are presented in Table 2. The reference mixture exhibited an average rebound number of 8.75 ± 1.23, while the EA mixture showed a comparable value of 8.63 ± 0.66. In contrast, the EP mixture presented the highest rebound number (10.75 ± 3.65), corresponding to an increase of approximately 23% compared with the reference mortar. The higher rebound values observed for the EP mixture indicate increased surface hardness of the mortar. This behavior can be associated with the presence of emery particles, which are characterized by high intrinsic hardness and may contribute to improved resistance of the surface layer to localized mechanical loading.

Table 2. Rebound number (R) values of the investigated mortars obtained from the Schmidt hammer test.

Mixture	Rebound number (mean ± SD)
REF	8.63 ± 1.23
EA	8.75 ± 0.66
EP	10.75 ± 3.65

3.3 Impact Resistance

The impact resistance of the mortars was evaluated using a drop-weight test (Table 3). The reference (REF) and EA mixtures failed at a drop height of 0.50 m, corresponding to an impact energy of approximately 24.5 J. In contrast, the EP mixture with emery powder resisted impact up to a drop height of 0.70 m, corresponding to an energy of approximately 34.3 J. This indicates an improved resistance to impact loading for the EP mixture.

Table 3. Impact resistance of the investigated mortars determined by the drop-weight test.

Mixture	Average damage width (mm)	Failure drop height (m)	Impact
energy (J) REF	28.27	0.50	24.5
EA	28.37	0.50	24.5
EP	28.83	0.70	34.3

3.4 γ-Ray Attenuation

The γ-ray shielding performance of the investigated mortars was evaluated by determining the linear attenuation coefficient (μ) at different photon energies. The results indicate that the attenuation coefficient decreases with increasing photon energy for all mixtures, which is consistent with the typical interaction behavior of ionizing photons with matter.

At lower photon energies (121.78 keV), the attenuation coefficients ranged between approximately 0.32 and 0.36 cm^{-1}, while at higher energies (1408.01 keV) the values decreased to approximately 0.11–0.12 cm^{-1}. Mortars incorporating emery exhibited slightly higher attenuation coefficients compared with the reference mixture.

Among the investigated mixtures, the EP mortar showed the highest μ values across all photon energies, followed by EA and REF. This behavior can be attributed to the higher specific gravity (and thus density) of EP mortar, followed by EA and REF, which increases the probability of photon interaction within the material. The results suggest that the incorporation of emery can enhance the radiation-shielding capabilities of cement-based mortars.

3.5 SEM Analysis

The microstructure of the investigated mortars was examined by scanning electron microscopy (SEM), while the elemental composition of selected regions was determined using energy dispersive spectroscopy (EDS). Representative SEM micrographs and the corresponding EDS analyses for the REF, EA and EP mixtures are shown in Fig. 3 (Table 4).

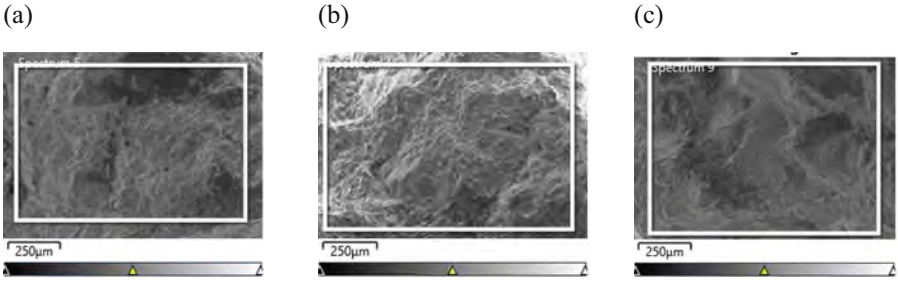


Fig. 3. Representative SEM micrographs of the investigated mortars: (a) REF, (b) EA and (c) EP.

Table 4. EDS elemental composition (wt%) of representative regions in the REF, EA and EP mortars

Element	REF	EA	EP
Na	1.87	3.16	1.05
Mg	2.05	1.04	1.99
Al	8.19	11.52	5.49
Si	34.12	41.23	36.66
S	3.92	2.31	4.21
K	1.85	5.21	0.79
Ca	48	35.53	49.81
Total	100	100	100

The reference mortar exhibits a typical hydrated cement matrix dominated by Ca and Si, which is consistent with the presence of calcium silicate hydrate (C-S-H) phases. The EA mixture presents a slightly more heterogeneous microstructure, with EDS analyses indicating relatively higher Si and Al contents in certain regions, likely associated with the influence of aggregate particles.

In contrast, the EP mortar shows a more compact and homogeneous matrix with fewer visible pores. The corresponding EDS spectrum is again dominated by Ca and Si, indicating typical cement hydration products. The denser microstructure observed for the EP mixture is consistent with its lower porosity and improved mechanical performance.

4 Conclusions

This study examined the effect of incorporating emery aggregates and emery powder in cement-based mortars, focusing on their influence on physico-mechanical properties, pore structure, surface hardness, and impact resistance. The results showed that the addition of emery, particularly in powder form, improves the overall mechanical performance of the mortars. The EP mixture exhibited the highest flexural strength and compressive strength at 90 days, showing increases of approximately 22% and 13%, respectively, compared with the reference mortar. A similar trend was observed for the dynamic modulus of elasticity, indicating increased stiffness of the cementitious matrix. Porosity measurements revealed that the EP mixture developed the densest microstructure, presenting the lowest open porosity after 90 days of curing. Therefore, the highest radiation-shielding performance was observed for the EP mixture. In addition, the specific gravity of the mortars increased with the incorporation of emery, reflecting the higher density of emery particles and contributing to the overall densification of the cementitious matrix. The rebound hammer and drop-weight impact tests further confirmed the improved mechanical response of the EP mixture, which exhibited higher surface hardness and greater resistance to impact loading compared with the reference mortar. SEM-DS observations showed that all mortars were dominated by Ca–Si-rich hydration products typical of hydrated cement systems. However, the EP mortar presented a more compact and homogeneous microstructure, consistent with the lower porosity and improved mechanical properties observed experimentally. Overall, the findings indicate that emery powder can effectively enhance the performance of cement-based renders by improving matrix densification and mechanical response, highlighting its potential use in high-performance construction materials.

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Rosin-Based Admixtures for Cementitious Materials

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Abstract. The ongoing search of sustainable and high-performance construction materials urges the investigation of bio-based admixtures. This research investigates the functionalization of cement composites using unmodified pine rosin (GR) and modified rosin ester: Pentaerythritol Ester of pine Rosin (PER)). This esterified derivative, selected for its enhanced thermal stability and compatibility, was incorporated at 0.5% and 1.5% by cement weight) to evaluate its potential as multifunctional performance modifier rather than cement replacement. The impact on both fresh (viscosity, setting time) and hardened state properties. The composites were assessed for mechanical performance (compressive strength), hygroscopic behavior (porosity, wettability, capillarity), and volume stability. The distinct chemical profile of PER, derived from natural pine rosin and processing imparted differentiated effects on the cement matrix studied by SEM/EDS. The research aims to identify the optimal rosin ester and dosage for enhancing hydrophobicity and to elucidate the underlying mechanism by which each admixture's organic chemistry modifies the composite's microstructure and final properties. This comparative analysis is a pre-liminary work that provides a critical foundation for the tailored application of specific rosin esters in developing advanced, eco-efficient cementitious materials.

Keywords: cement · esterification · rosin · pentaerythritol rosin ester

1 Introduction

Colophony (rosin) is a highly available residual organic admixture derived from pine resin or as a paper industry by-product [1], with potential for developing low environmental-footprint cement composites. Rosin exhibits surface-active properties that influence cement hydration and microstructure evolution [2]. Fang et al. [3] showed that rosin promotes air entrainment and reduces water absorption, improving aggregate-cement affinity and modifying porosity [4]. Its carboxylic acid functionality enables interaction with cement hydration products [5], while esterified derivatives such as

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pentaerythritol ester (PER) provide improved resistance to oxidation and alkali attack [6].

Despite these promising findings, the effects of rosin on cement paste hydration, rheology, mechanical performance, and durability remain insufficiently understood. This study investigates the incorporation of resin rosin at low participation levels (0.5% and 1.5%) in cement pastes, focusing on fresh properties, mechanical behavior, and hygroscopic characteristics, aiming to advance the understanding of bio-based admixtures for sustainable cementitious materials.

2 Materials and Methods

2.1 Rosin Modification

Pinus pinaster resin rosin was esterified with pentaerythritol (270–275 °C, purity ≥99.9%, Sigma-Aldrich, St. Louis, USA), (1,1-Di-tert. -butyl)-4-hydroxyphenyl) methyl) ethylphosphonate) (Irganox 1425, BASF, CAS Number: 65140-91-2), TBM-6 (4,4′-Thiobis(2-tert-butyl-5-methylphenol)) (358.54 g/mol, Sigma-Aldrich) chemicals were obtained.

Esterification of natural rosins with pentaerythritol is significant because the resulting quaternary ester structure provides steric hindrance that prevents ester bond hydrolysis in the alkaline pore solution of hydrating cement. Pentaerythritol ester rosin synthesis was conducted according to previous research [5]. Optimum synthesis conditions were determined using a pentaerythritol/rosin molar ratio of 1/1, TBM-6/rosin at 1.0% w/w, and Irganox 1425/rosin at 0.5% w/w. The reaction was carried out under mechanical stirring and nitrogen atmosphere, while the acid number was measured every 2 h according to ASTM D 465-05. FT-IR spectra were obtained for characterization.

FT-IR analysis of the modified and unmodified rosins was done using a PerkinElmer Frontier spectrometer with an attenuated total reflectance (Attenuated Total Reflectance - ATR) accessory. Spectra were collected over the 4000–500 cm^{-1} at a resolution of 4 cm^{-1}.

2.2 Cement Pastes Composition

Five cement paste mixes were prepared using cement (CEM I42.5) and rosin in different ratios. Paste consistency (6 ± 2 mm) and setting times were determined using a Vicat apparatus according to EN 196-3. Viscosity was measured with an ICAR Rheometer, while heat of hydration was monitored for 2 days using a TAM Air calorimeter. Prismatic specimens (25 × 25 × 100 mm) were cast in metallic molds, demolded after 24 h, and cured at 20 °C and 90% RH until testing.

Table 1. Mixture compositions of cement pastes (parts per weight)

Mixture	CEM I42.5	W/B	Rosin (%) by weight of cement	modification	μ (Pa.s)
0%	1	0.3	–	–	18.6
0.5%	1	0.3	0.50%	no	30.4
1.5%	1	0.3	1.50%	no	24.5
0.5%m	1	0.3	0.50%	yes	402
1.5%m	1	0.3	1.50%	yes	149.5

2.3 Cement Pastes Testing

At 7 and 28 days, compressive strength was measured using a 150 kN hydraulic testing machine. Volume stability was monitored after demolding under dry conditions (21 °C, 60% RH) until stabilization. Sample density was determined according to EN 1015-10. Hygroscopic behavior was evaluated through open porosity (RILEM CPC 11.3), capillary absorption (EN 1015-18), and contact angle measurements using a KRÜSS DSA100 Drop Shape Analyzer. The microstructure at 28 days was analyzed using Scanning Electron Microscopy - Energy Dispersive Spectroscopy (SEM-EDS).

3 Results and Discussion

The FT-IR spectra of unmodified and modified rosin samples are shown in Fig. 1. The spectra are generally similar, indicating that the primary rosin backbone is retained after modification. In natural rosin, the band at ~2922 cm^{-1} is assigned to aliphatic C–H stretching vibrations of methyl and methylene groups, characteristic of the diterpene-based hydrocarbon structure [7], while the absorption at 1687 cm^{-1} corresponds to the C=O stretching vibration of carboxylic acids. Following esterification with pentaerythritol, the carbonyl region changes markedly. In pentaerythritol ester rosin (PER), the band near 1700 cm^{-1} is attributed to ester carbonyl stretching, confirming successful ester formation. PER also exhibits a broad O–H stretching band at 3322 cm^{-1}, indicating that some pentaerythritol hydroxyl groups remained unreacted.

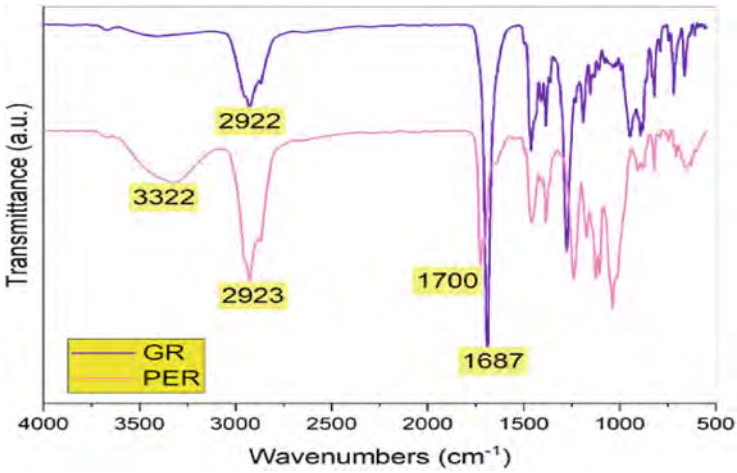


Fig. 1. FT-IR analyses of modified (PER) and unmodified rosin (GR) samples

The heat of hydration results obtained by TAM air calorimetry are shown in Fig. 2. The main hydration peak appears between 10 and 13 h, associated with C-S-H formation and C_3S dissolution. Compared with the control paste, rosin addition shifts the main peak to later times, indicating hydration retardation. The modified samples (0.5%m and 1.5%m) exhibit a more pronounced delay and broader peaks. The rheological behavior of the mixtures (Table 1) depended on rosin content. Low unmodified rosin dosage (0.5%) increased viscosity, while higher dosage (1.5%) slightly reduced it. Modified rosin caused a strong viscosity increase at 0.5% due to stronger interactions with cement and water, whereas at 1.5% the viscosity decreased compared with the 0.5% modified mixture.

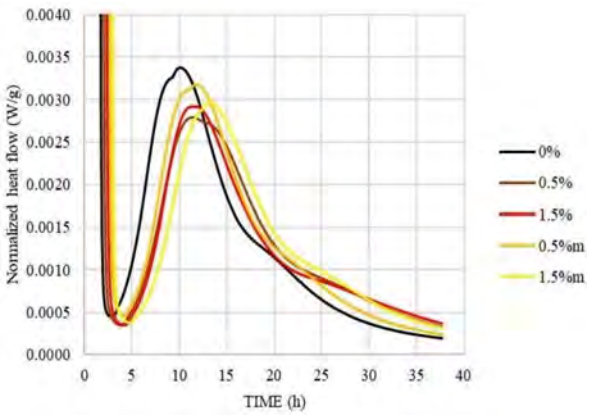


Fig. 2. Heat of hydration of cement pastes with or without added rosin

Setting time of the cement pastes is given in Fig. 3. The reference paste (0%) begins setting at about 230 min. The mixture of 0.5% rosin shows a slight delay (~260 min), while 1.5% rosin caused a more significant delay (~320 min). In contrast, mixtures with modified rosin set earlier than the corresponding unmodified ones. The 0.5% modified rosin paste began setting at about 220 min, slightly earlier than the reference, while the 1.5% modified rosin mixture sets at ~300 min, earlier than the 1.5% rosin paste but still later than the control. These results are consistent with the heat of hydration measurements.

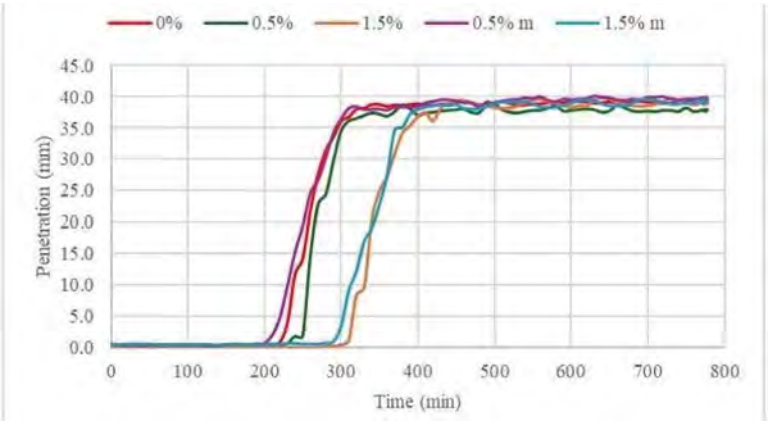


Fig. 3. Setting time of cement pastes with or without added rosin

Figure 4 presents the results for the volume stability of the mixtures. Higher additions of 1.5% rosin or 1.5%m reduced volumetric changes, improving dimensional stability. This is likely due to rosin's hydrophobicity, which limits moisture loss and drying shrinkage. Mixtures with 0.5% rosin behaved like the reference, showing minimal effect. Rosin's impact on shrinkage increased with dosage.

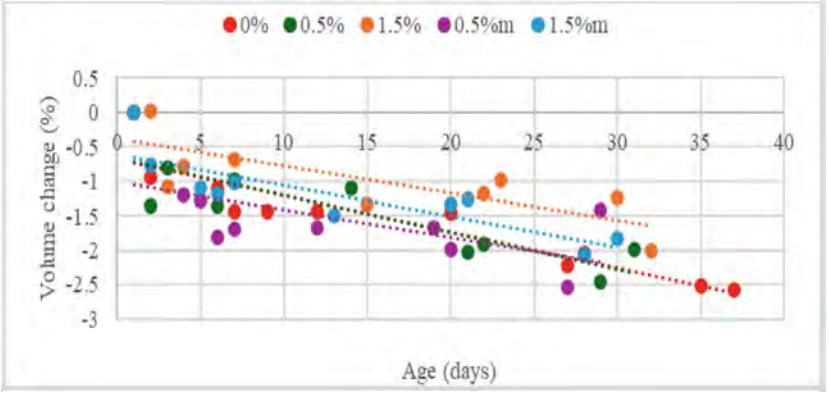


Fig. 4. Shrinkage of cement pastes with or without added rosin

The compressive strength (Fig. 5) showed that at 7 days, the ref. mixture (0%) reaches 65.50 MPa under compression. The addition of 0.5% rosin reduced strength by 14%, while 1.5% rosin caused a significant decrease to 33.78 MPa (−48%). For the modified rosin mixtures, 0.5%m shows 64.74 MPa, almost equal to the ref., whereas 1.5%m reached 39.16 MPa, still higher than the unmodified mixture. At 28 days, all mixtures show increased strength. The ref. reaches 76.49 MPa, while 0.5% rosin attains 68.62 MPa (−10%) and 1.5% rosin only 42.98 MPa (−43%). The modified rosin mixtures perform better: 0.5%m reached 75.25 MPa, nearly matching the ref., and 1.5%m achieved 60.79 MPa, significantly higher than 1.5% unmodified mixture.

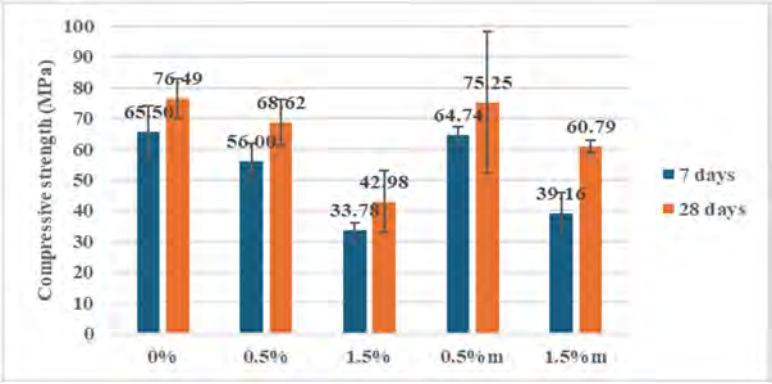


Fig. 5. Compressive strength of cement pastes with (0.5%, 1.5%) or without (0%) rosin

As regards capillary absorption (Fig. 6), the addition of rosin greatly reduced capillary water uptake, with values less than 1/3 of the ref., showing improved resistance to water ingress. Modified rosin (0.5%m and 1.5%m) further lowered absorption, indicating enhanced hydrophobic performance, mainly due to better compatibility with cement. It resulted in more effective pore blocking and low capillary continuity.

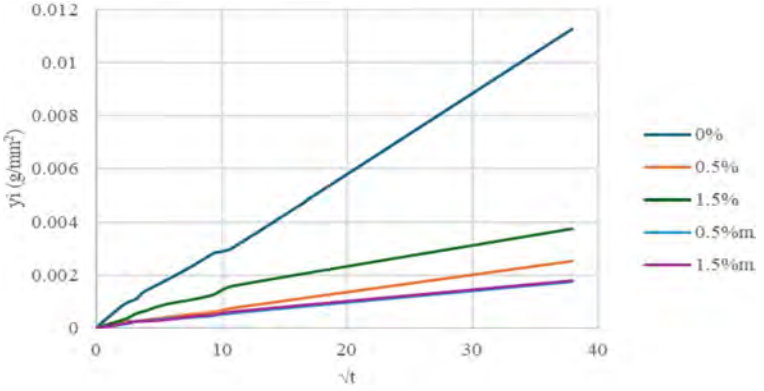


Fig. 6. Capillary absorption of cement pastes with or without added rosin

The density, porosity and contact angle of the mixtures are shown in Table 2. The reference mixture (0%) showed a slight density decrease (1.99 → 1.95 g/cm^3) and porosity reduction (26.88 → 18.26%) over 28 days. 0.5% unmodified rosin slightly lowered density but greatly reduced porosity (7.69%). 1.5% unmodified rosin gave lower densities (1.85–1.83 g/cm^3) and higher early-age porosity (29.14%), decreasing to 12.46% at 28 days. Modified rosin mixtures (0.5%m, 1.5%m) showed higher densities and lower porosity, especially at 7 days (16.02% and 8.92%). At 28 days, porosity remained low (11.56% and 10.93%), indicating a denser cement matrix from improved dispersion and hydration interaction. The ref. mixture (0%) had a contact angle of 33.78°, showing a relatively hydrophilic surface. 0.5% and 1.5% rosin reduced it to 28.53° and 17.20°, while modified rosin mixtures reached 19.86° (0.5%m) and 15.97° (1.5%m). Despite lower porosity and capillary absorption in modified mixtures, contact angles did not increase, indicating water resistance is driven by pore structure, not surface wettability. Surface hydrophilicity depends on surface energy and chemical groups (–OH, –COOH, –NH_2, Ca^{2+}). These groups attract water, lowering contact angles and promoting rapid wetting.

Table 2. Density and porosity values of cement pastes with or without added rosin.

Mixture	Density (g/cm)^3		Porosity (%)		Contact angle (^{o})
	7 days	28 days	7 days	28 days	28 days
0%	1.99	1.95	26.88	18.26	33.78
0.5%	1.95	1.93	24.19	7.69	28.53
1.5%	1.85	1.83	29.14	12.46	17.20
0.5%m	1.97	1.97	16.02	11.56	19.86
1.5%m	1.94	1.93	8.92	10.93	15.97

The presence of rosin (0.5% and 0.5 m%) caused a more homogenized structure with restricted porosity, as seen in Fig. 7 by SEM-EDS. The composition of the mixtures was similar, but the crystallization was compact in relation to the reference structure. The amount of rosin didn't seem to improve the situation, as the same formations were observed in the samples containing 1.5% and 1.5%m resin.

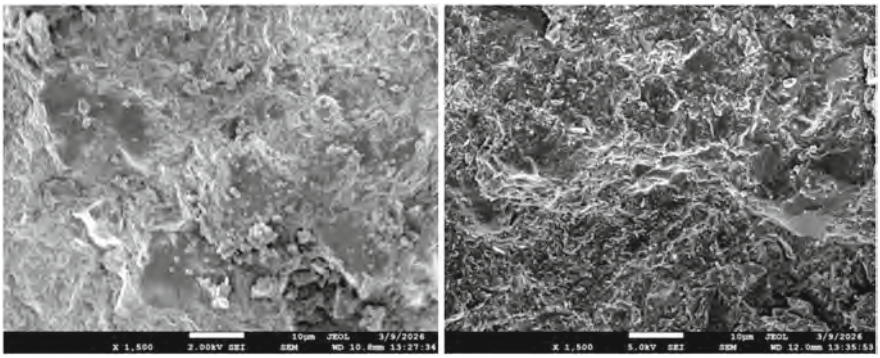


Fig. 7. SEM-EDS analysis of samples with 0.5% (left) and 0.5%m (right)

4 Conclusions

The main experimental results demonstrate that the chemical modification of rosin plays a decisive role in balancing the fresh-state behavior and long-term performance of cementitious composites. In particular, the modified rosin admixture (PER) achieved a significant reduction in capillary absorption and porosity while maintaining compressive strength values close to the reference mixture at low dosage (0.5%), indicating improved compatibility with the cement hydration products and the formation of a denser microstructure. In contrast, unmodified rosin caused a more pronounced retardation effect and strength reduction, especially at higher dosages, highlighting the importance of esterification in enhancing the stability and dispersion of bio-based additives within alkaline cement systems. SEM observations further support these findings, revealing a more homogeneous and compact matrix in mixtures containing modified rosin.

From a sustainability perspective, the proposed rosin-based admixtures represent a promising renewable alternative to conventional petroleum-derived chemical additives, as they are derived from naturally available pine resin and industrial byproducts. Their ability to improve water resistance and dimensional stability at very low incorporation levels contributes to the development of more durable cementitious materials with potentially extended service life and reduced maintenance demands, supporting more sustainable and resource-efficient construction practices.

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Beyond Buildings: Cascading Co-products and Carbon Pool Uplift in Adaptive Wood Design

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Abstract. Decarbonizing the built environment requires more than substituting concrete and steel with mass timber. The climate impact of wood construction depends on how harvested biomass is allocated across its entire lifecycle—especially the co-products and underutilized species typically excluded from long-lived applications. This paper introduces a design and modelling framework that integrates cascading co-products with species substitution to expand the usable pool of wood resources while increasing long-term carbon storage in buildings. Current life-cycle assessments and harvested wood product models treat sawdust, bark, pulp chips, and off-cuts as marginal flows destined for short-lived uses or disposal, forfeiting substantial carbon-storage potential. By redirecting these co-products into durable products such as wood-fibre insulation, panel cores, and engineered composites—and pairing these with species substitutions informed by the Forest-Building trait framework—we demonstrate how functionally adaptive construction assemblies can both broaden material flexibility and uplift regional carbon pools. Using five wall assemblies as prototypes, we compare functional performance, species utilization, material composition, and resilience metrics across cascading and adaptive strategies. Results show that integrating co-product flows with multi-species design can significantly increase carbon retention while maintaining or improving thermal and structural performance. The findings highlight that the carbon benefits of timber construction are not inherent but arise from systemic design choices across species selection, product recipes, and end-of-life pathways.

Keywords: Forest-Building · cascading co-products · carbon pools · adaptive wood design · circular construction

1 Introduction

Wood is increasingly promoted as a sustainable construction material due to its capacity to store biogenic carbon, yet its long-term climate benefits depend on far more than substituting concrete and steel. Wood is wasted at every stage of its life cycle—from harvest to milling, construction, use, and end-of-life—and these losses coincide with growing stress on forest ecosystems under climate change. Ensuring the continued availability and

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climate performance of wood therefore requires strategies that both minimize biomass waste and expand the range of species and wood components that can be incorporated into long-lived construction products. While previous research has explored opportunities to reuse wood residues [1] and to expand the use of underutilized species [2], these strategies have often been examined independently. However, the carbon impact of wood construction ultimately depends on how harvested biomass is allocated across its entire lifespan [3]. Species selection, processing methods, cascading flows, and end-of-life (EoL) pathways all influence how much carbon remains stored in buildings rather than being lost through short-lived uses or disposal. What is needed is an integrated framework that brings these approaches together to guide material choice in adaptive, low-carbon wood construction.

This paper introduces the Functional-Trait Cascading Co-Product Design (FT-CCD) framework as a holistic method for specifying wood assemblies that maximize carbon storage and increase adaptive capacity. The framework builds on two complementary domains of research. First, it draws from the concept of cascading use, which examines the full range of co-products generated throughout wood's life cycle—including bark, sawdust, shavings, pulp chips, off-cuts, and trim ends—and identifies pathways for reintegrating these into long-lived applications. Although substantial co-product streams are produced at primary and secondary manufacturing stages, many still flow into short-lived or landfill pathways, particularly at end-of-life where data remain limited and infrastructure for reuse is underdeveloped [4]. Expanding cascading pathways requires both better characterization of EoL flows and design strategies capable of integrating heterogeneous material inputs into structural and environmental components. Second, the framework incorporates the Forest-Building (FB) trait-based approach, which groups tree species according to shared functional building traits that influence performance attributes such as strength, stiffness, density, durability, and thermal behavior [3]. By identifying species with comparable traits, the FB framework enables informed species substitution—especially the use of underutilized, low value, or early-successional species—without compromising performance or constructability. The indicators of resilience help quantify how well species combinations support ecological resilience and adaptive capacity under changing forest conditions [5].

Combining co-product utilization with trait-based species substitution expands both the material palette and the lifespan of harvested biomass. Cascading co-products reduces dependence on newly harvested wood and keeps carbon circulating through durable components, while species substitution aligns material sourcing with forest resilience, diversifies supply chains, and reduces reliance on a small set of commercially dominant species. Together, these form the basis of the FT-CCD framework: a flexible, carbon-aware approach to wood construction that responds to both material availability and ecological change. To operationalize the FT-CCD framework, we apply it to five prototype wall assemblies that vary in species composition, co-product integration, and structural strategy. Through these assemblies, we evaluate how combining cascading flows with trait-based diversity can shape building performance, reduce waste, and support long-term carbon retention. This integrated perspective highlights the need for life-cycle-oriented design in contemporary timber construction—one that synchronizes material systems with forest dynamics in a changing climate.

2 Methodology

The methodological approach consisted of two parallel components: (1) mapping and quantifying cascading co-products across the wood life cycle, and (2) integrating species substitution using the Forest-Building (FB) trait-based framework. These components were then combined in the development of five prototype wall assemblies used to test the Functional-Trait Cascading Co-Product Design (FT-CCD) framework.

2.1 Co-product Flow Mapping Across Lifecycle Stages

To characterize the availability and type of co-products generated throughout wood's lifespan, we developed a material-flow model that synthesizes data from multiple sources. Lifecycle stages were structured in alignment with conventional life cycle assessment (LCA) boundaries, including: (a) forest operations, (b) primary manufacturing, (c) secondary manufacturing, (d) construction, and (e) end-of-life (EoL) [6].

Co-product categories for each stage were identified through a synthesis of: existing lifecycle stage diagrams, published co-product characterizations, documentation and technical specifications from wood-processing facilities, and site visits to mills and fabrication centers. Table 1 summarizes these co-product streams and reports their approximate share of input flows (by mass or volume, depending on reported units) [7]. Because co-product estimates originate from diverse industrial studies, the values reflect the internal distribution within each stage rather than summing to 100% across stages. This table serves as the basis for determining which co-products are available for reintegration into construction assemblies. Where empirical data was lacking—particularly at the EoL stage—we inferred co-product quantities by analogy with earlier stages that use similar processes. For example, recycled or reused EoL wood often requires cutting, planning, or mulching, which generate co-products similar in type and proportion to those produced during primary and secondary manufacturing. These analogues were used to develop conservative, process-based estimates of EoL co-product streams.

2.2 Trait-Based Species Substitution

Species substitution was carried out using the Forest-Building (FB) trait-based framework, which groups species according to functional building traits [3]. These traits include strength, stiffness, durability, density, and other performance characteristics relevant to engineered and structural wood design. To evaluate the adaptive potential of different species combinations, we applied three FB ecological-functional indicators: Functional Redundancy (FR): the extent to which multiple species can perform similar structural or environmental functions. Functional Diversity (FD): the range of functional traits represented across species, contributing to adaptive capacity under changing conditions [5]. Resilience Index (RI): a composite metric integrating FR, FD, and species richness, used to assess system-level adaptability. Species substitutions were selected to maintain required performance characteristics while broadening the material pool

to include underutilized and lower-value species. These substitutions help reduce pressure on dominant commercial species and align construction material choice with forest resilience objectives.

Table 1. Breakdown of wood co-product sources and relative quantity across life cycle stages.

Lifecycle Stage	Product Type (Product/Co-product)	Processing Co-products	Share of Input flows (%)
Forest	Product	Round wood	95
	Co-Product	Slash (Residue)	5
Primary manufacturing	Product	Structural product (lumber / plywood)	43–50
	Co-Product	Bark	8–9
	Co-Product	Planer shavings	6
	Co-Product	Sawdust	5–6
	Co-Product	Pulp chips	19–35
	Co-Product	Peeler cores	9
	Co-Product	Hog fuel	8–14
	Co-Product	Trim ends	<1
	Co-Product	Chipper fines	<1
	Co-Product	Wood waste	<1
Secondary Manufacturing	Product	Engineered wood products	60–80
	Co-Product	Shavings	5–6
	Co-Product	Wood residues	30–35
Construction	Product	Installed product	54
	Co-Product	Offcuts	30–35
	Co-Product	Scraps	5–10
	Co-Product	Sawdust	2–4
	Co-Product	Damaged goods	6
End of Life	Co-Product	Bad physical quality items	69
	Co-Product	Good physical quality items	39
	Co-Product	Damaged beyond repair goods	2

2.3 Assembly Prototyping Using the FT-CCD Framework

To demonstrate how cascading co-products and trait-based species substitution can be combined in practice, we developed five prototype wall assemblies representing varying levels of adaptive material use. The panels were designed to evaluate how different combinations of species, co-products, and structural strategies influence both building performance and ecological metrics. Panel 1 represents baseline construction using conventional SPF lumber and no co-product integration. Panels 2–4 incrementally incorporate species substitution and selected co-products (e.g., engineered aspen members, mixed-species CLT, and LSL manufactured from hardwood fibers). Panel 5 represents the highest level of FT-CCD integration, using seven species and five types of co-products across structural and envelope components. For each assembly we evaluated: wood volume, species composition, use of co-products, thermal performance (R-value), and FB indicators (FR, FD, RI). This allowed us to compare how the FT-CCD framework influences both functional building performance and ecological adaptability. Assembly details are summarized in Table 2, and the cascading and substitution logic for Panel 5 is illustrated in Fig. 1.

Table 2. Co-products and species substitution wall panel breakdown.

Assembly	Adaptation Degree	Wood Volume (m^3)	R-Value	Species Composition % (total volume)		SS	CP	FR	FD	RI
1. Baseline Stud Wall	Business as Usual (BAU)	0.14	15	Balsam Fir 40 White Spruce 60		No	No	Low	Low	Low
2. Engineered Aspen Stud Wall (24″ o.c.)	Low	0.18	26	Aspen dominant + Red Pine cladding		Yes	No	Low	Mid	Low
3. Mixed-Species CLT Wall	Moderate	0.31	15	Tamarack / Pine / Birch / Aspen mix		Yes	No	Low	High	Mid
4. Single 2 × 2 LSL Stud Wall (8″ o.c.)	Moderate	0.22	19	Aspen Birch Poplar	75 10 15	Yes	Yes	High	Mid	Mid
5. Larsen Truss Wall	High	0.38	35	Tamarack Aspen Hemlock Pine Cedar Maple Birch	26 21 23 12 10 4 4	Yes	Yes	High	High	High

SS: Species Substitution, CP: Co-Product Use, FR: Functional redundancy, FD: Functional diversity, RI: Resilience Index

2.4 Linking Co-products to Performance Requirements

Co-product integration was guided by the performance requirements of each wall component. For example: wood-fibre insulation was selected due to its suitability for thermal regulation and its ability to incorporate fine-particle co-products; plywood gussets and OSB webs were used to reintegrate dimensional off-cuts and chips into load-distributing elements; dense-pack timber fill was employed to utilize shredded or mulched co-products with suitable moisture and thermal characteristics. This ensured that co-products were not simply added as material substitutions but were purposefully integrated based on their physical properties and potential performance contributions.

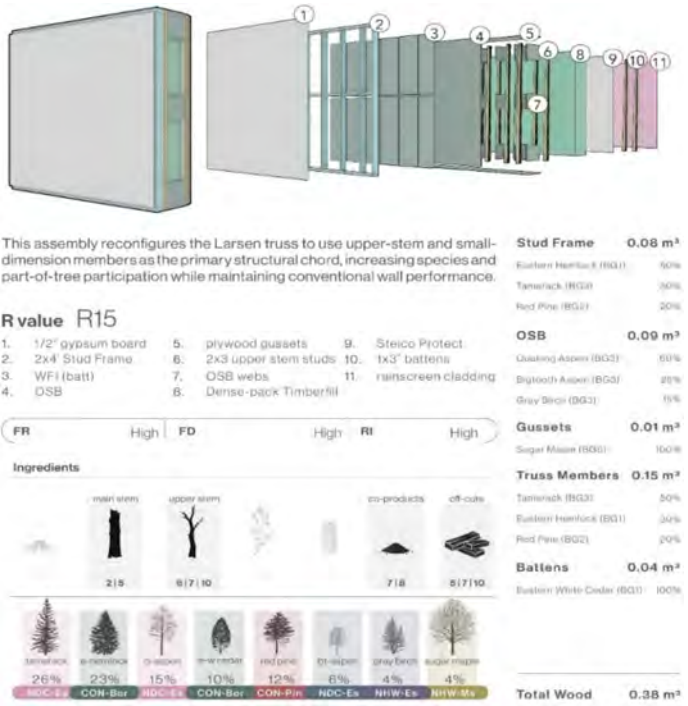


Fig. 1. Demonstrating Cascading Co-product Design framework: Co-product and species substitution breakdown of Larsen Truss Wall (Panel 5).

3 Results and Analysis

Primary and secondary manufacturing produce substantial volumes of pulp and milled chips suitable for durable applications (e.g., wood-fibre insulation, composite panel cores). Additional co-products—bark, peeler cores, planer shavings, and sawdust—comprise an underutilized resource stream. Construction-stage off-cuts and clean dimensional scraps can be reused directly in blocking or battens or recycled into secondary

products. Based on process analogues, up to ~98% of co-products produced across the life cycle could be diverted from landfill through reuse, recycling, or (where appropriate) bioenergy recovery, thereby retaining biogenic carbon within long-lived applications. Realizing this diversion requires clean collection, logistics for sorting and storage, and EoL pathways that enable recirculation rather than disposal.

The five prototype wall assemblies demonstrate how cascading co-products and trait-based species substitution influence ecological, thermal, and structural performance.

Panel 1—Baseline SPF Stud Wall. Relies on white spruce and balsam fir, with no cascading. Exhibits low FR, FD, and RI, reflecting minimal adaptive capacity and a narrow ecological/material basis.

Panel 2—Engineered Aspen Stud Wall. Introduces early-successional hardwoods (engineered aspen; red pine cladding), modestly increasing FD while maintaining comparable performance; no co-products used.

Panel 3—Mixed-Species CLT Wall. Combines tamarack, pine, birch, and aspen in one element, substantially increasing FD and modestly improving FR without compromising structural utility**.**

Panel 4—LSL Stud Wall with Co-products. Integrates both substitution and cascading. LSL from aspen/birch/poplar fibers raises FR and RI, demonstrating how co-products and species diversity reinforce each other.

Panel 5—Larsen Truss Wall (Full FT-CCD Integration). Incorporates five co-product types (WFI batts, OSB webs, plywood gussets, dense-pack timber fill, and 1 × 3 battens) across five of eleven components and draws on eight species. This approach achieves the highest FR, FD, and RI, and the strongest thermal performance (R-35). Although total wood volume is highest, a substantial share comes from streams that would otherwise be downcycled or landfilled, maximizing carbon retention in long-lived components.

Across all assemblies, the results reveal consistent and reinforcing trends: (1) Cascading co-products expands the usable wood pool, reducing demand for newly harvested material and keeping carbon stored in long-lived forms. (2) Species substitution increases ecological resilience, enabling construction systems to reflect the diversity and structure of future climate-stressed forests rather than relying on a narrow set of commercially dominant species. (3) Assemblies integrating both strategies (Panels 4 and 5) demonstrate superior performance, reflected in higher FR, FD, RI, often without sacrificing thermal or structural performance.

4 Towards Adaptive, Carbon-Uplifting Construction

Integrating cascading co-products with trait-based species substitution substantially increases the adaptive capacity and carbon-storage potential of wood construction. Mapping co-product flows and applying the FB framework to species selection reveals how material and assembly-level decisions influence ecological resilience and long-term carbon outcomes. Assemblies that combine both strategies achieve the highest FR, FD,

and RI while delivering strong thermal envelope performance. These systems rely less on newly harvested commercial lumber and make greater use of underutilized species and co-products that would otherwise be downcycled or landfilled, thereby maintaining more biogenic carbon in long-lived components and aligning construction practices with climate-stressed forest realities. Advancing this approach requires governance, supply-chain logistics, and EoL infrastructure that support clean recovery, sorting, and reuse of co-products; future work should refine EoL quantification, extend FT-CCD to other building systems, and integrate dynamic, multiscale carbon accounting.

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Advancing Circular Economy Practices through the Experimental Valorization of Spent Garnets (SG) for Sustainable Building Material Development

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Abstract. Garnet sands represent highly used industrial abrasives that, after their operational life, generates substantial quantities of waste as Spent Garnets (SG). However, despite its potential, much of this material remains unutilized, ending up in landfills, creating both environmental challenges and untapped resource opportunities. In the context of the circular economy, SG waste can be considered a valuable secondary resource, in line with the principles of reuse, recycling, and sustainable development of materials. The recovery of these industrial wastes might have a contribution to reducing the extraction of natural aggregates, minimizes environmental impact, and contributes to the creation of innovative building materials with a positive environmental impact. This study explores experimental research directions for the utilization of SG waste, generated by Abrasive waterjet material processes (AWJ), focusing on its application as a partial replacement for natural sand in cement-based mortars and concrete. The research highlights both ecological and technical benefits, including potential improvements in mechanical properties and durability, as well as reduced pressure on natural resources. By systematically evaluating material properties, performance in different composite matrices, and potential for large-scale adoption, this work aims to provide a basis for sustainable SG materials design. The results indicate that, with targeted experimental programs, standardized quality assessments, and supportive policy frameworks, SG waste can become an integral component of circular construction practices, converting it into a valuable industrial by-product that supports both environmental and economic goals.

Keywords: Spent Garnet wastes (SG) · abrasive waterjet cutting (AWJ) · Circular economy · green concrete

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1 Introduction

The construction sector is both a cornerstone of economic development and a significant contributor to environmental pressures. The extraction of natural aggregates, high energy consumption, and large-scale waste generation challenge global sustainability targets. In response, the circular economy (CE) has emerged as a guiding framework aimed at maintaining materials in productive use for as long as possible, minimizing waste, and reducing dependence on virgin resources.

One promising yet underexplored opportunity lies in the valorisation of mineral industrial by-products generated outside the construction domain as natural aggregate replacement in cementitious materials and products used in construction [1]. Abrasive waterjet (AWJ) cutting technology is widely used in manufacturing industries for precise cutting of metals, ceramics, composites, and stone. The process relies on mineral abrasives that lose their cutting efficiency after use [2, 3]. Garnet minerals are the main abrasives used in (AWJ) cutting due to their crystalline structure and chemical versatility. Although typically red or reddish-pink, garnets can also be green, orange, yellow, or black. Their hardness, sharp grain edges, and controlled grain-size distribution enable stable abrasive flow without focusing-tube blockages, improving cutting quality, speed, and accuracy [4, 5]. The resulting spent garnet (SG) typically becomes a waste stream. Despite its predominantly inert mineralogical composition, SG is frequently landfilled, creating disposal costs and missed resource opportunities [2, 3].

The integration of SG into construction cementitious materials and products presents a dual advantage, graphically emphasised in Fig. 1. First, it diverts waste from disposal pathways, offering positive environmental and economic impact from the waste management perspective. Second, it partially substitutes natural aggregates, reducing extraction pressures.

However, for such integration to move beyond conceptual appeal, it must be supported by experimental evidence demonstrating technical feasibility and performance reliability.



Fig. 1. CE Framework for the Valorization of Spent Garnet Waste in Cementitious Materials

Based on the synthesis of experimental results on SG incorporation into cement-based materials (mortars), this paper aims to propose a practical methodology for the circular economy valorisation of industrial SG mineral wastes as partial substitutes for natural aggregates in cementitious composites. The proposed approach seeks to support the transition from laboratory-scale research toward practical implementation in the construction sector. Several key aspects must be considered to ensure the feasibility of this valorisation pathway. These include: (1) the physical and chemical characterization of AWJ spent garnets, such as particle size distribution, mineralogical composition, and potential contaminants; (2) the evaluation of mechanical and durability performance of SG-modified cementitious composites; and (3) the application of a validation methodology to confirm material performance and compliance with relevant construction standards.

2 Synthetic Overview of Research Concerning Spent Garnet Wastes as Sand Substitution in Cementitious Materials

2.1 Global Research on Spent Garnet Waste as Sand Replacement in Cementitious Materials

In recent years, spent garnet (SG) waste has attracted increasing attention as a potential partial or full replacement for natural sand in cementitious materials. Scientific studies have evaluated its suitability for conventional cement-based composites [1, 6, 7], concrete incorporating various mineral additions [8], high-strength concrete [9], and concrete exposed to elevated temperatures [10, 11]. SG has also been investigated in lightweight composites [11, 12] and mortar mixtures [13, 14]. In addition, Baeră et al. examined cement-based mortars as promising construction materials for the incorporation of SG waste [2, 3, 15–21]. Beyond traditional cement systems, SG has also been explored in alkali-activated cementitious materials (AACMs), including geopolymer mixes where garnet waste partially replaces natural aggregates. Such approaches were studied by Muttashar et al. [22–24] and Danish et al. [25, 26]. Furthermore, garnet tailings have been considered as potential supplementary additions in concrete [27], mainly due to their latent hydraulic potential, which may contribute to improving the performance of the binding system. A common, general methodology in these studies involves preparing a control mix (mortar or concrete) and evaluating mixtures with incremental SG sand replacement levels (egg. 25%, 50%, 75%, and 100%). The results consistently indicate that SG is a feasible substitute for natural sand in cement-based composites.

2.2 Current Status of Spent Garnet Waste Research in Romania

In Romania, research on the integration of garnet waste into cementitious materials has been carried out within the first research axis of project PN 23 35 04 01, "*Development of innovative engineering solutions for eco-intelligent construction products by an efficient capitalization of additions generated by local industries"* part of the Nucleu Programme under the National Research, Development and Innovation Plan 2022–2027, "ECODIGICONS", funded by the Romanian Ministry of Research, Innovation and Digitalization.

The project is based on the premise of valorizing industrial by-products and residues through their innovative incorporation into construction materials, in line with Circular Economy (CE) strategies in Romania [2, 15]. The project aims to identify scientific, technical, and applied solutions for the national construction infrastructure, aligned with European Union objectives and national strategic frameworks such as SNEC 2022 [28], the National Strategy for Research, Innovation and Smart Specialization (SNCISI 2022–2027) [29], and the Recovery and Resilience Plan for Romania (PNRR) [30]. It involves the development of technological algorithms for the construction sector and related industries through efficient collaboration among key stakeholders, including academia and research institutions, entrepreneurs, industry users and end-consumers, suppliers, and social, economic, and political actors, including local and central authorities.

The relevant results covering a comprehensive four-year research program examining SG wastes derived from single-cycle AWJ processes and their incorporation into regular mortars as fine-grain partial replacement in cement-based construction composites have been previously reported in the referenced publications [2, 3, 15–21] and collectively support the integration methodology proposed in this study, also covering the key aspects previously mentioned in the Introduction section.

3 Practical Methodology for the Circular Economy Valorization of Industrial Mineral Wastes in Cement-Based Materials

3.1 Methodological Framework for Circular Valorization of SG Waste

The proposed methodological framework follows a structured circular economy pathway for the valorization of spent garnets (SG) generated from abrasive waterjet (AWJ) cutting processes as a partial replacement for natural aggregates in cement-based construction materials. The graphical representation of the proposed SG integrating pathway from "cradle", meaning the waste producer to the new potential life cycle, is presented in Fig. 2. The process begins with the *identification, collection, and representative sampling of SG waste from industrial sources*. The collected material undergoes conditioning procedures, including drying, sieving, and removal of impurities, to obtain a consistent particle size distribution suitable for construction applications. Subsequently, the *conditioned SG is subjected to comprehensive physicochemical characterization*, including particle size analysis, density determination, chemical composition, and microstructural evaluation. These investigations assess the compatibility of SG with cementitious matrices and determine its potential as a secondary aggregate. Based on the obtained material properties, *experimental mix designs are developed to incorporate SG as a partial replacement for natural fine aggregates in cement-based materials.* The resulting mixtures are evaluated through *mechanical and durability testing, including compressive strength, flexural strength, water absorption, and other performance indicators relevant to construction applications.*

Following laboratory validation, the *optimized formulations undergo pilot-scale evaluation and industrial collaboration to assess production feasibility*. This stage facilitates technology transfer to industry, enabling the integration of SG-based materials into existing manufacturing processes. Finally, the *developed products undergo regulatory*

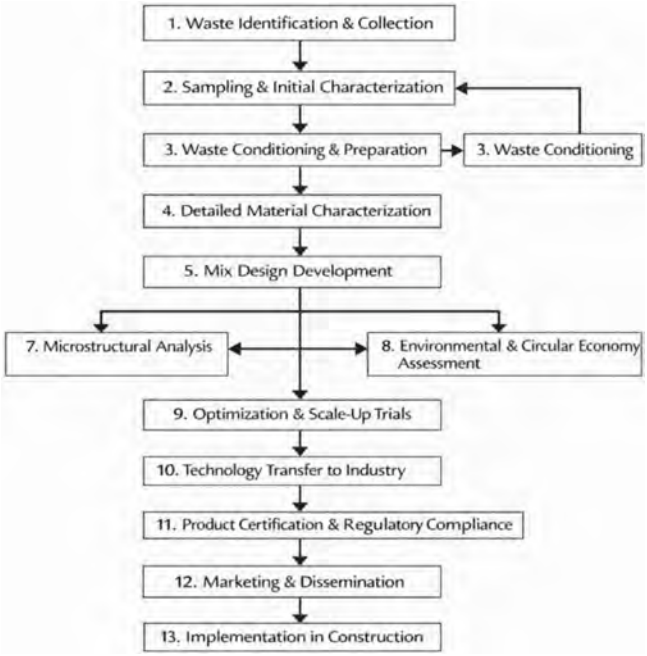


Fig. 2. Circular economy methodology for the valorization of industrial mineral SG wastes as partial replacement of natural aggregates in cement-based materials

compliance and certification procedures, followed by *market introduction and practical implementation in construction applications*. Through this systematic process, SG waste is transformed into a valuable secondary resource, contributing to waste diversion, reduced natural aggregate extraction, and the development of sustainable building materials within a circular economy framework.

3.2 Implementation of the Proposed SG Integration Methodology: Achieved Results

The results obtained, synthesized in Fig. 3, so far indicate significant progress in implementing the proposed SG integration methodology. Existing studies have covered the physical and chemical characterization of AWJ spent garnets, including particle size distribution, mineralogical composition, and potential contaminants, as well as the evaluation of the mechanical and durability performance of SG-modified cementitious composites. Furthermore, a validation methodology has been applied to confirm material performance and verify compliance with relevant construction standards [3].

3.3 Conclusions: Future Steps Toward Industrial Implementation of SG Valorization

Building on the laboratory validation results, the ongoing research focuses on advancing the procedural pathway required for the technological transfer of SG-based construction



Fig. 3. Experimental validation framework for the integration of AWJ spent garnet (SG) waste as partial aggregate replacement in cement-based mortars

materials and products. This stage involves targeted laboratory investigations aimed at product development through experimental testing, multi-criteria data analysis, comparative performance evaluation, and compositional optimization. In parallel, a technological assessment is conducted to identify compatible production technologies, including equipment requirements, technological sequences, pre- and post-processing conditions, and critical operational parameters necessary for calibrating the intended production flows. Complementary legislative and regulatory consultations are also undertaken, involving a systematic review of relevant national and European standards, technical norms, and regulatory frameworks, in order to define the technical characteristics, performance thresholds, and reference values required for prototype validation and subsequent industrial implementation. Furthermore, the short- to medium-term objectives targets product certification in accordance with relevant EN legislation, and the implementation of the developed materials in pilot construction applications under real operating conditions. Collectively, these steps aim to facilitate the transition from laboratory to industrial practice, enabling the effective circular valorization of SG wastes as secondary raw materials and supporting the broader adoption of sustainable, resource-efficient construction materials. The proposed pathway advances circular economy practices in construction by valorizing industrial mineral wastes and reducing dependence on natural aggregates.

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Bio-Based Composite Materials for Systemic Circularity in the Built Environment: Pathways, Performance, and Design Implications

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Abstract. Advancing sustainability and circularity in the built environment requires the development of material systems capable of supporting transitions away from linear and resource-intensive construction models. Bio-based composite materials are emerging as viable alternatives to conventional construction materials due to their reduced environmental impacts and potential contribution to circular building systems. However, their application in structural and envelope components requires further investigation regarding material performance, composition, and environmental efficiency.

This article presents an analytical and experimental study exploring the potential of bio-design approaches and bio-based materials for the development of sustainable and regenerative construction systems. The research focuses on Ulva-based bio-composite materials derived from marine biomass collected from eutrophic Mediterranean coastal zones. The study examines the transformation of Ulva algae into functional composite constituents through washing, desalination, drying, and mechanical processing prior to their incorporation into bio-based formulations. The developed materials were evaluated in terms of mechanical performance, thermal conductivity, and environmental impact. The results demonstrate the potential of Ulva-based composites for non-structural and insulating building applications while contributing to the valorization of marine biomass associated with eutrophication phenomena.

This research provides an integrated assessment of the performance and environmental implications of Ulva-based materials and contributes to the development of low-impact bio-based composite systems for circular and regenerative construction applications.

Keywords: Biomaterials · Circularity · Building environment · environmental regeneration · Ulva algae

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1 Introduction

The construction sector is a major contributor to greenhouse gas emissions, resource depletion, and waste generation worldwide. Conventional materials such as concrete, steel, and synthetic insulation are associated with energy-intensive production processes and linear lifecycles. Transitioning toward more sustainable construction practices requires a fundamental rethinking of material systems, emphasizing circularity, efficiency, and environmental compatibility [1, 2].

Bio-based composite materials have emerged as promising alternatives due to their renewable origin, carbon sequestration potential, and compatibility with low-energy manufacturing processes [3–5]. However, most current developments remain limited to circular economic approaches, focusing primarily on waste reduction and recycling strategies. Advancing sustainability and circularity in the built environment requires the development of material systems capable of supporting systemic transitions away from linear, resource-intensive construction models. Circular bio-sourced composite materials, produced from renewable fibers, agricultural residues, and emerging bio-based polymer matrices, offer a robust pathway to reduce embodied carbon, enhance resource efficiency, and enable regenerative material flows [6–8]. This paper extends these approaches by integrating a regenerative design framework based on the concept of the "design of the living", exploring Ulva algae as an emergent biomaterial in Mediterranean ecosystems. In regions such as Sfax (Tunisia), recurrent Ulva blooms represent both ecological imbalance and a valuable bio-resource, offering potential for the development of lightweight bio-based composites with insulating properties and reduced environmental impact [9, 10]. Through an experimental and analytical investigation, this study evaluates the incorporation of Ulva biomass into bio-based mortars, lightweight concretes, and composite systems intended for non-structural and insulating building applications. The research examines the processing of Ulva biomass and evaluates the developed composites in terms of mechanical behavior, thermal conductivity, and environmental performance. The objective is to assess the potential of Ulva-based composites in supporting low-impact and circular construction systems while contributing to the valorization of marine biomass associated with eutrophication phenomena.

2 Materials and Methods

2.1 Experimental Study and Research Approach

This research is positioned within a regenerative bio-design framework inspired by the concept of the "design of the living", which explores the integration of biological resources into circular and sustainable material systems for the built environment [11, 12]. The study combines analytical reflection and experimental investigation to evaluate the potential of Ulva-based bio-composites as sustainable materials for regenerative design and construction applications [13]. The methodological approach aims to demonstrate how marine biomass associated with eutrophication phenomena can be transformed into a locally sourced material resource for sustainable construction applications. In this context, the study investigates both the environmental valorization of Ulva algae and the material performance of the developed composites.

Ulva biomass was collected from coastal accumulation zones in eutrophic Mediterranean environments, particularly in the region of Sfax (see Fig. 1). The collected algae were selected due to their local abundance and their environmental impact on coastal ecosystems. The valorization of this biomass seeks to transform an environmentally harmful accumulation into a renewable resource within a circular and regenerative design approach.



Fig. 1. Coastal eutrophication phenomenon in Sidi Mansour, Sfax (Tunisia)

2.2 Preparation and Experimental Testing

The collected biomass was subjected to a preparation protocol including washing, desalination, drying, and mechanical grinding to obtain fine particles suitable for composite integration. Additional materials included silica-rich sand and mineral binders. Several formulations incorporating Ulva particles at different proportions, ranging from 10% to 90% by weight, were developed and cast into molds under controlled laboratory conditions. The methodology combined material processing, specimen preparation, and performance evaluation to assess the mechanical, thermal, and environmental characteristics of the developed composites. Mechanical testing showed that formulations containing higher proportions of Ulva powder exhibited enhanced deformation behavior compared to the control sample composed solely of sand (see Fig. 2).

In particular, the formulation containing 50% Ulva powder demonstrated a yield strength of approximately 0.2 MPa and a modulus of elasticity of 3 MPa, indicating improved load-bearing capacity suitable for non-structural applications [13]. Thermal conductivity values ranging between 0.06 and 0.12 W/m·K indicate promising insulating properties for lightweight construction systems and energy-efficient building envelopes. Environmental assessment also demonstrated a potential reduction in embodied carbon of up to 60% through the partial substitution of conventional materials with marine biomass.

The study demonstrates the potential of Ulva-based composites as low-impact materials capable of supporting circular and regenerative construction strategies. Despite these promising results, several challenges remain regarding moisture sensitivity, variability in biomass composition, and long-term durability.

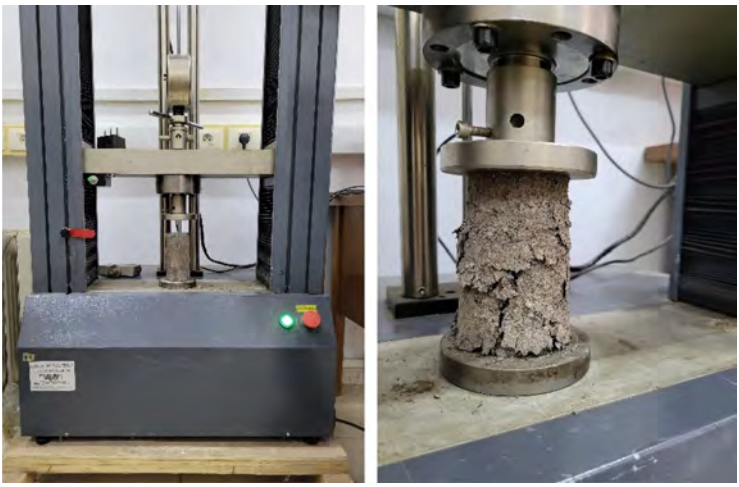


Fig. 2. Compression testing of Ulva-based composite specimens to evaluate mechanical performance.

3 Fabrication Strategies for Ulva-Based Composite Materials

The development of bio-based composite materials for the construction sector is increasingly associated with emerging fabrication technologies that enhance both material performance and environmental efficiency. In the context of Ulva-based composites, these approaches support the transformation of marine biomass into functional construction systems while contributing to regenerative design strategies. These research perspectives were extended toward practical architectural applications through a collaboration with the local company SOIB for the development of compacted blocks incorporating Ulva biomass. Following several experimental trials, a prototype formulation combining silica sand, Ulva powder, local soil, and a limited proportion of cement binder was developed (see Fig. 3). The blocks were naturally dried and designed to interlock without the use of additional mortar, contributing to lightweight construction systems with reduced material consumption.

Bio-based additive manufacturing represents a promising approach for the fabrication of lightweight and geometrically optimized building components. Unlike conventional subtractive methods, additive manufacturing enables the controlled deposition of material only where structurally required, thereby reducing waste and improving resource efficiency [14]. When applied to Ulva-based composites, these techniques may facilitate the integration of algae-derived particles or biopolymer matrices into printable formulations adapted to architectural applications. Potential applications include prefabricated wall panels, lightweight insulating components, and adaptive façade systems designed to improve environmental performance. In addition, localized production systems based on bio-based additive manufacturing may contribute to reducing transportation impacts while promoting the use of locally available biomaterials such as Ulva algae.



Fig. 3. Ulva-based composite block illustrating material fabrication and structural application

Research on fiber architecture and hybrid composite systems further highlights the importance of internal material organization in improving composite performance. In Ulva-based materials, the combination of algae-derived particles with lignocellulosic fibers or mineral matrices can enhance interfacial bonding, crack resistance, and structural stability. Gradient structures and multilayer composite configurations may also improve thermal and mechanical behavior while reducing overall material consumption [15]. This approach demonstrates that the performance of Ulva-based composites depends not only on material composition but also on fabrication and design strategies aligned with circular and regenerative construction systems.

4 Results and Discussion

Ulva integration represents a shift toward regenerative materials. Unlike terrestrial fibers, Ulva contributes to marine ecosystem restoration. It introduces multifunctional properties such as antimicrobial behavior and UV resistance. Challenges include scalability and durability. The integration of Ulva algae into bio-based composites represents a significant advancement beyond conventional plant-based materials. Unlike terrestrial biomass, Ulva contributes to marine ecosystem restoration by reducing nutrient loads and mitigating eutrophication.

From a materials science perspective, Ulva introduces unique properties such as anantimicrobial activity, UV resistance, and biodegradability. These characteristics position Ulva-based composites as multifunctional materials bridging construction and environmental engineering. Despite these advantages, challenges remain in terms of durability, standardization, and industrial scalability. Future research should focus on hybrid material systems, long-term performance evaluation, and integration into industrial production processes. This study demonstrates that bio-based composites are not merely alternative materials but systemic enablers of circular construction.

Key insights:

- Material performance can be tailored through additive selection
- Circularity depends on both material design and construction methods

– Local resource availability plays a critical role

However, scaling up remains limited by:

– Standardization gaps
– Regulatory barriers
– Lack of industrial integration

Future research should focus on:

– Hybrid bio-mineral systems
– Long-term durability testing
– Integration into digital design workflows

5 Conclusion

Bio-based composite materials, specifically Composites material structures and bricks incorporating natural fibers and agricultural residues, offer a viable pathway toward circular construction systems.

Their advantages include:

– Reduced environmental impact
– Improved thermal performance
– Compatibility with circular lifecycle strategies

By combining material innovation with circular design principles, these composites can contribute to a transformative shift in the built environment.

Ulva-based bio-composites offer a promising pathway toward regenerative construction systems. By combining circular economic principles with ecological restoration strategies, these materials can contribute to sustainable and resilient built environments. This research demonstrates the potential of transforming environmental challenges into opportunities for innovation.

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Bio-Circular Concrete: Valorization of Agricultural Ash and C&D Waste for Structural Applications

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Abstract. Vojvodina, widely recognized as the breadbasket of Serbia, generates substantial quantities of harvest residues, representing an underutilized resource with strong potential to offset the consumption of non-renewable materials. As biomass combustion becomes increasingly prevalent, the amount of generated ash continues to rise, offering new opportunities for its valorization in accordance with circular construction principles. At the same time, many existing buildings are approaching the end of their service life, contributing to the growing volume of construction and demolition (C&D) waste. These converging material streams create a promising basis for developing sustainable, low-carbon building components. Within the experimental program, four concrete mixtures were produced in which wheat-straw ash served as a partial cement replacement, while recycled concrete aggregate was employed as a substitute for course natural aggregate. Laboratory testing demonstrated that the mechanical performance of these eco-efficient concretes met the required standards, confirming their suitability for structural applications. As a proof of concept, a load-bearing masonry block was manufactured, showcasing the feasibility of integrating agricultural residues and C&D waste into contemporary construction materials. The findings highlight that the synergistic use of biomass ash and recycled aggregates provides a viable pathway toward reducing the reliance on primary resources while maintaining essential mechanical properties.

Keywords: Circularity · Biomass Ash · C&D waste · Concrete · Masonry Block

1 Introduction

Due to the rapid depletion of non-renewable energy resources and construction raw materials, together with concerns over global warming and greenhouse gas emissions, energy efficiency and sustainable development have become key priorities in modern construction. In response, the construction industry is increasingly adopting environmentally

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responsible practices. Consequently, research efforts focus on developing innovative materials and technologies that reduce the environmental footprint of buildings without compromising structural integrity or functionality.

The construction sector is responsible for nearly 40% of global CO_2 emissions [1], highlighting the urgent need for sustainable construction materials, particularly in the context of rapid urbanization and population growth. Environmentally responsible construction practices not only reduce environmental impacts but also provide economic benefits through improved energy efficiency and reduced operational costs. One promising approach is the incorporation of recycled and waste-derived materials into concrete mixtures. The use of industrial and agricultural by-products as supplementary cementitious materials (SCM) helps address waste management issues while reducing the consumption of conventional cement. Among these materials, biomass ashes from agricultural residues have attracted increasing attention due to their pozzolanic potential [2–4]. In addition, the replacement of natural aggregates (NA) with recycled concrete aggregates (RCA) reduces natural resource depletion and the environmental burden associated with aggregate extraction and transportation.

In this study, the development of innovative hollow concrete masonry blocks incorporating waste materials is investigated. Such approaches have become increasingly common in modern sustainable construction practice [5–8]. The proposed eco-efficient concrete was produced using wheat straw ash, obtained from the combustion of agricultural biomass originating from the region of Vojvodina, as a high-volume cement replacement (50%), while RCA was used as a complete substitute for coarse NA. By simultaneously replacing both binder and aggregate, the study aims to develop environmentally friendly concrete mixtures with reduced consumption of primary raw materials while maintaining adequate mechanical and thermal performance.

The mechanical performance of the developed eco-concretes was evaluated through compressive strength testing, while the most promising mixture was used to produce a load-bearing hollow masonry block. In addition to mechanical properties, the thermal performance of the block was assessed to examine its potential application in energy-efficient masonry construction. Particular attention was given to comparing the developed block with widely used commercial masonry units, such as porous clay "climate blocks", one of the most common masonry solutions in Serbia. Accordingly, the objective of this study was to develop an eco-efficient masonry unit with mechanical and thermal properties comparable to commercially available blocks.

2 Experimental Research

2.1 Materials

Portland cement (PC) used in this study was produced by the Lafarge cement plant in Beočin, Serbia. The cement had a specific gravity of 3.10 g/cm^3 and a Blaine fineness of 4000 cm^2/g.

Wheat straw ash (WSA) was employed as a supplementary cementitious material (SCM). The ash was supplied by "Mitrosrem", Sremska Mitrovica, Serbia. The chemical composition of WSA is presented in Table 1. The material is characterized by a high

content of reactive silica and a high level of fineness (Blaine fineness of 6500 cm^2/g), indicating a strong potential for the pozzolanic reaction.

Table 1. Chemical composition of wheat straw ash.

	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	MgO	CaO	SO_3	P_2O_5	Content Cl	Reactive SiO_2
CWP	69.1	0.2	1.7	0.1	13.0	2.5	5.8	0.2	1.7	0.06	67.1

The following types of aggregate were employed:

- Fine aggregate: natural river sand, with a particle size of 0–4 mm, fineness modulus of 2.88, density of 2.65 g/cm^3, and water absorption of 1.0%;
- Coarse aggregates: (1) natural river aggregate, with particle size fractions of 4–8 mm (density of 2.65 g/cm^3 and water absorption of 0.7%) and 8–16 mm (density of 2.65 g/cm^3 and water absorption of 0.6%); (2) recycled concrete aggregate (RCA) of unknown origin with the same particle size fractions and the density of 2.285 g/cm^3. The water absorption of the RCA fractions (4–8 mm and 8–16 mm) was 5.4% and 4.2%, respectively,

Tap water was used for the production of all concrete mixtures.

2.2 Methods

The compressive strength of concrete was determined in accordance with the standard SRPS EN 12390-3. The tests were performed on cube specimens with an edge length of 150 mm at ages of 28, 60, and 90 days (3 cubes for each mixture and each age).

The individual compressive strength values and the bulk density of masonry units were determined in accordance with SRPS EN 771-3, using full-size masonry blocks.

The thermal conductivity of the masonry block was determined according to ISO 6946 (calculation-based method). The overall thermal resistance of the block was calculated as the arithmetic mean of the upper and lower thermal resistance limits.

2.3 Concrete Composition

The experimental study was conducted on four different concrete mixtures. The reference concrete, denoted as A0, was prepared using NA, with PC as the sole binder.

Mixture B0 was produced with 50% cement replacement by WSA, while mixtures A100 and B100 were prepared using RCA as coarse aggregate. The mix design of all concrete mixtures, regardless of the aggregate type, was defined based on the following criteria:

- the total binder (cement or a blend of PC and WSA) was fixed at 400 kg/m^3;
- the water-to-binder (w/b) ratio was set to 0.45.

Based on the water absorption values of the RCA fractions, an additional amount of water was introduced into the mixtures containing RCA in order to pre-saturate the recycled aggregate and ensure comparable effective water-to-binder ratios.

The mixture designations and the quantities of component materials for each concrete mixture are summarized in Table 2.

Table 2. Labels and component materials for concretes.

	m_c	m_{wsa}	m_w	Δm_{w1}	m_{hrwr}	$m_{na,I}$	$m_{na,II}$	$m_{na,III}$	$m_{rca,II}$	$m_{rca,III}$
A0	400	/	180	/	2.4	850	412	513	/	/
B0	200	200	180	/	2.4	825	400	498	/	/
A100	400	/	180	43.0	1.60	781	/	/	291	459
B100	200	200	180	43.0	2.0	758	/	/	283	446

3 Results and Discussion

3.1 Compressive Strength of Concrete

The results of the compressive strength tests are illustrated in Fig. 1.

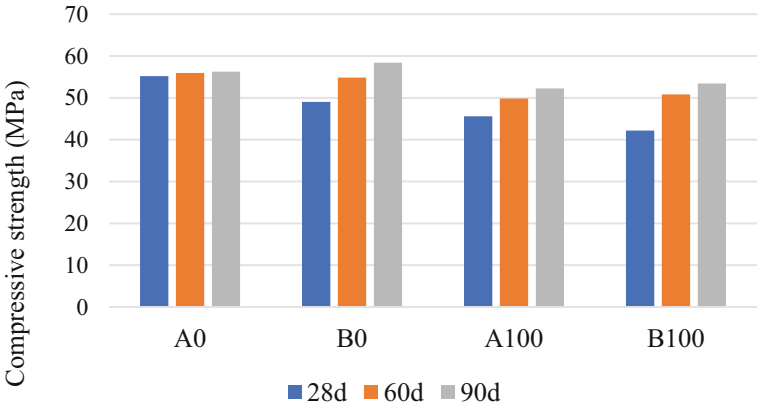


Fig. 1. Compressive strength of the tested concrete mixtures at 28, 60, and 90 days.

The substitution of NA with RCA generally resulted in a reduction in the compressive strength of concrete at all testing ages. This decrease in strength can be attributed to the inferior mechanical properties of RCA compared to NA. On the other hand, the replacement of cement with WSA led to an 11% reduction in compressive strength at the age of 28 days. This decrease is primarily associated with the dilution effect, i.e., the reduced content of hydrated cement paste and the lower amount of hydration products [9, 10]. As a result of pozzolanic reaction, concretes containing WSA exhibit

a significant strength gain over time. Consequently, the concrete containing 50% WSA (B0) exceeded the compressive strength of the reference concrete by 4% at 90 days. It can therefore be concluded that at 90 days, the positive contribution of WSA compensates for the adverse effect of RCA on compressive strength. Accordingly, the eco-efficient concrete incorporating 50% WSA and 100% RCA attains compressive strength levels comparable to those of the reference concrete produced with NA and conventional PC. Given its favorable mechanical performance comparable to the reference concrete, this eco-efficient concrete was selected for producing a masonry block, representing the next stage of the experimental investigation.

3.2 Masonry Block Preparation

The nominal dimensions of the masonry block (25 × 40 × 19 cm), as well as the size and arrangement of the cavities, were defined based on the geometry of contemporary concrete masonry units. The selected dimensions correspond to typical formats used in modern masonry construction. The wall thickness was set to 2 cm, considering the maximum aggregate size to ensure proper placement and compaction of the fresh concrete mixture (Fig. 2).

The internal cavities were formed using expanded polystyrene (EPS). The introduction of internal voids is a common approach in ceramic and concrete hollow blocks, aimed at reducing unit weight and improving thermal insulation performance [11–14]. The blocks were manufactured in the laboratory using wooden molds. After casting, the concrete was cured under controlled laboratory conditions before testing.



Fig. 2. Concrete casting into molds and the resulting masonry block.

3.3 Physical and Mechanical Properties of the Masonry Block

The hollow concrete masonry blocks were demolded 24 h after casting and immersed in water for curing. After 28 days, the blocks were removed and prepared for compressive strength testing. The compressive strength and bulk density of the masonry units were determined in accordance with SRPS EN 771-3 using full-size blocks. The representative compressive strength was calculated as the average of the test results, which are presented in Table 3.

Table 3. The bulk density and compressive strength of the masonry block.

	Bulk density [kg/m^3]	Mean compressive strength [MPa]	Equivalent compressive strength [MPa]	Normalized compressive strength [MPa]
D100	1195	15.3	18.4	19.7

Based on the obtained compressive strength results, the masonry block can be classified as a Category II load-bearing unit ($f_m \geq 6$ MPa), indicating its suitability for structural masonry applications.

3.4 Thermal Conductivity of Masonry Block

In addition to mechanical performance, the thermal properties of the masonry block were evaluated to assess its suitability for energy-efficient masonry construction. The thermal conductivity was calculated according to ISO 6946. The characteristic cross-section of the block, including layer dimensions and designations, is shown in Fig. 3.

The block consists of thermally homogeneous and non-homogeneous layers arranged parallel to the heat flow. The overall thermal resistance was calculated as the arithmetic mean of the upper and lower limits, from which the thermal conductivity of the masonry block was determined. The thermal conductivity of concrete was assumed according to ISO 6946 as 1.434 W/(mK).

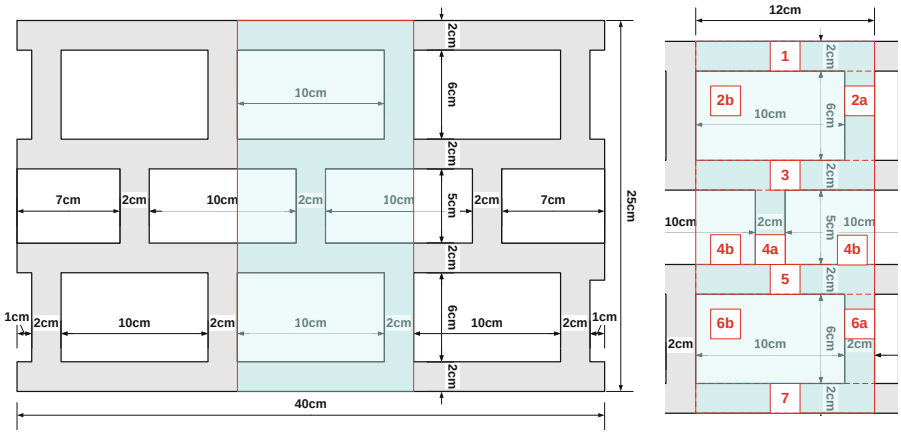


Fig. 3. Characteristic cross-section of the block used for thermal resistance calculation.

The calculated thermal conductivity of the block was 0.122 W/(mK). As this value lies between 0.06 and 0.30 W/(mK), the blocks can be classified as thermo-insulating structural masonry elements with adequate mechanical and thermal performance.

3.5 Comparative Analysis

The results in Table 4 compare the developed eco-efficient masonry block with a widely used commercial clay "climate block" of the same nominal dimensions.

The developed block exhibited a compressive strength of 15.3 MPa, higher than that of commercial porous clay blocks (≈13 MPa), indicating its suitability for load-bearing masonry. The bulk density of the eco-block was 1195 kg/m^3, compared to ≈700 kg/m^3 for the ceramic climate block, mainly due to the nature of the concrete matrix. Despite the higher density, the eco-block shows significantly lower thermal conductivity, indicating improved thermal insulation performance, which can be attributed to EPS-filled cavities and the optimized block geometry.

Table 4. Comparison of properties of the eco-efficient block and a commercial block.

	Eco block (this study)	Commercial clay climate block
Bulk density [kg/m^3]	1195	700
Compressive strength [MPa]	15.3	13.0
Thermal conductivity [W/(mK)]	0.122	0.22
Photographic illustration		

Overall, the comparison indicates that the developed eco-efficient block achieves comparable or superior mechanical performance with improved thermal insulation, confirming its potential as a sustainable alternative to conventional masonry units.

4 Conclusions

Based on laboratory testing of physical and mechanical properties and analytical evaluation of thermal performance, the following conclusions can be drawn for eco-efficient masonry blocks produced from locally available waste materials:

- Hollow masonry blocks with cavities filled with insulation material based on expanded polystyrene, produced using concrete in which recycled crushed concrete was used as aggregate and approximately 50% of the cement was replaced with biomass ash, exhibited satisfactory compressive strength. Therefore, they can be used for load-bearing external walls or infill walls in framed structures.
- The obtained value of thermal conductivity indicates that the analyzed blocks can be applied without additional thermal insulation in regions with mild to moderately warm climates, such as Mediterranean climates. In colder climatic regions, however, an additional layer of thermal insulation would be required to satisfy energy-efficiency requirements.

- The adopted block dimensions increase construction efficiency compared to conventional masonry units. Due to the larger format and tongue-and-groove interlocking, fewer units are required per square meter of wall, reducing construction time and thermal bridges.
- The surface of the blocks is relatively smooth, reducing the need for extensive plastering. Consequently, only a final finishing layer may be required, which can further simplify construction procedures and reduce material consumption.

Finally, the developed masonry units demonstrate that locally available waste materials, including agricultural biomass ash and recycled concrete aggregates, can be successfully incorporated into structural masonry elements, contributing to reduced consumption of primary raw materials, lower environmental impact, and the advancement of sustainable and circular construction practices. Moreover, when compared with commonly used porous clay "climate blocks" of the same nominal dimensions, the developed eco-efficient block exhibits higher compressive strength and significantly improved thermal insulation performance, indicating that it represents a technically viable and environmentally sustainable alternative to conventional masonry units used in contemporary construction.

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Development of Improved Mechanical Characteristics Through Mineralization in Mortars with Metallurgical Slags and Olivine

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Abstract. The use of industrial by-products as partial substitutes for cement and natural aggregates has emerged as a promising approach to reducing CO_2 emissions. The purpose of this study was to investigate the use of industrial by-products in developing low-carbon mortar mixtures. The study examined the effect of mineralization (via accelerated carbonation), a process that has recently emerged as a promising method for both passive carbon absorption and improving the microstructure of cementitious materials. The alternative materials used were steel slag and ladle furnace slag, by-products of the steel industry, and olivine, a by-product of mining processes. Emphasis was placed on reducing the cement and natural aggregate content by incorporating these industrial by-products, with the aim of producing more environmentally friendly mixtures while maintaining good mechanical performance. Four different mortars with 80% by weight replacement of cement with steel slag, ladle furnace slag, or hydrated lime were prepared and tested for their mechanical and physical properties after curing in a natural environment or after mineralization. The tests included compressive strength, dynamic modulus of elasticity estimation, porosity, water absorption and specific gravity, as well as thermogravimetric analysis and stereoscopic observation. The combined use of steel slag and ladle furnace slag as supplementary cementitious materials demonstrated significant potential for CO_2 uptake, with a compressive strength increase of over 20% after accelerated carbonation.

Keywords: Mineralization · Accelerated Carbonation · Steel Slag · Ladle Furnace Slag · Olivine

1 Introduction

Over the past decades, there has been a constant effort toward decarbonizing the construction industry. At the same time, the extraction of raw materials and their energy-intensive processing have significantly increased the sector's environmental footprint [1]. The use of industrial by-products as alternative construction materials has proven to be a viable solution, as they have a low environmental footprint and help reduce natural resource

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consumption [2]. Well-known materials such as fly ash and silica fume have been successfully used to replace cement, while others, such as steel slag, have mostly been used as aggregates [3, 4]. However, various other readily available materials produced on a large scale from industrial processes, such as olivine and different types of slag, could also be used in construction [5, 6].

Another approach to decarbonization involves carbon capture and storage technologies. In the construction sector, this can be achieved through accelerated carbonation or mineralization of construction materials or products [7, 8]. Carbonation is the process in which carbon dioxide (CO_2) reacts with calcium hydroxide ($Ca(OH)_2$) to produce calcium carbonate ($CaCO_3$). The typical natural carbonation process is a slow chemical kinetic reaction, which is why, in recent years, a new method called accelerated carbonation has been developed.

Accelerated carbonation practices can be divided into pre-carbonation of construction materials and mineralization of construction products for strength development. Steel slag and olivine have both shown potential for carbon sequestration in either process [9, 10]. Liu et al. [11] reviewed the use of pre-carbonated steel slag as a cement substitute and found that it has significant carbon sequestration potential and can improve mechanical strength. In contrast, Zhang et al. [12] and Bremen et al. [13] have shown that the carbon uptake of construction products is significant.

This research aims to assess the strength improvement of mortars with ladle furnace slag and steel slag as the main binders, and olivine or steel slag as aggregates, after accelerated carbonation.

2 Materials and Methods

2.1 Materials

Steel slag and ladle furnace slag (LFS), by-products of a steel industry in Thessaloniki, Greece, were used as binders. To improve their reactivity, both were ground to a granulometry below 100 μm. The ground steel slag, at 60% by weight of the total binder, was combined with 20% ordinary Portland cement and 20% hydrated lime or ground ladle furnace slag to produce ternary mortars.

Unground steel slag, with a particle size of 0–5 mm, served as aggregate at 50% by weight, combined with either natural river sand or olivine aggregates of similar gradation, originating from magnesia mining operations in the area of Vasilika, Greece.

Table 1 presents the four different mortar mixtures produced using a ratio of 0.65: 1: 5.3 for water: binder: aggregate. All mortars had the same water-to-binder ratio.

Initially, ten specimens were produced for each mixture using 100 × 100 × 100 mm moulds (a total of 40 specimens) for testing at 1, 28, and 56 days after casting. After demoulding one day after casting, the specimens were placed in a humidity chamber with a relative humidity (RH) of 90% for 28 days.

After the curing period, the specimens were separated into two groups, which were kept under different curing conditions. For each mixture, three specimens were used as reference samples and tested at 28 days of curing.

The two different curing conditions were under laboratory conditions at a constant temperature of 24 °C and relative humidity of approximately 50% for 4 weeks (56d N)

Table 1. Mortar design in ratios by weight.

Mortar constituents	HLS	HLO	LFSS	LFSO
Ground steel slag	0.60	0.60	0.60	0.60
Ordinary Portland cement	0.20	0.20	0.20	0.20
Hydrated lime	0.20	0.20	–	–
Ground ladle furnace slag	–	–	0.20	0.20
Water	0.65	0.65	0.65	0.65
Steel slag fine aggregate	2.65	2.65	2.65	2.65
Natural river sand	2.65	–	2.65	–
Olivine fine aggregate	–	2.65	–	2.65

and in an accelerated carbonation chamber at a constant temperature of 24 °C, relative humidity of 99%, pressure of 1 atm, and 40% CO_2 concentration for 1 week (56d CO_2).

After the first round of tests, a new batch of specimens was produced using the same mixtures. The purpose of this batch was to evaluate the properties of the specimens over a longer period (1 month and 3 months).

The curing conditions for these specimens were laboratory conditions at a constant temperature of 24 °C and relative humidity of approximately 50% for 9 weeks (90d N), and an accelerated carbonation chamber at a constant temperature of 24 °C, relative humidity of 99%, pressure of 1 atm, and 2.5% CO_2 concentration for 7 weeks (90d CO_2).

2.2 Testing Methods

After curing, the specimens were subjected to physicomechanical and analytical testing to determine the effect of carbonation. Compressive strength was measured on the cubic specimens with a 300 kN Universal Testing Machine (WAW-300E). The ultrasonic pulse velocity v was determined with a Proceq Pundit Lab sonometer, and the values obtained were used to estimate the dynamic modulus of elasticity E_D of the mortars using Eq. (1), where ρ is the apparent specific gravity of the mortar, as obtained by weighing and measuring the dimensions of the specimens.

$$E_D = \rho \times v^2 \tag{1}$$

The RILEM CPC 11.3 recommendation was used to determine the porosity, water absorption, and specific gravity of the hardened mortars. Thermogravimetric analysis with a Netzsch STA 449 F5-Jupiter apparatus was used to assess the carbonation process, along with stereoscopic observation using a Leica M10 stereoscope.

3 Results and Discussion

3.1 Porosity, Water Absorption and Specific Gravity

Figures 1, 2 and 3 present the porosity, absorption and specific gravity of all test mortars at 90 days respectively.

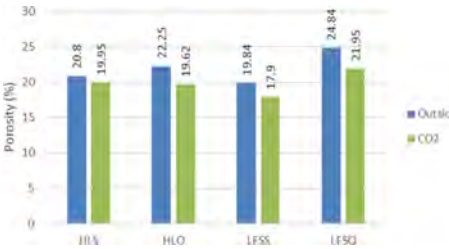


Fig. 1. Porosity of mortars at 90 days.

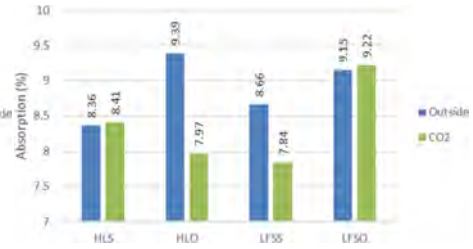


Fig. 2. Water absorption of mortars at 90 days.

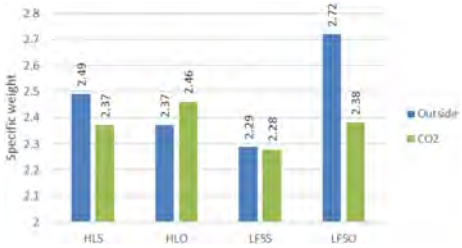


Fig. 3. Specific gravity of samples at 90 days.

Porosity values were relatively high (18–25%) across all mixtures, indicating low internal cohesion and mechanical strength. However, samples that underwent carbonation consistently displayed lower porosity – by about 5% for hydrated lime and about 7.5% for LFS samples – compared to the laboratory-conditioned ones, confirming the pore-filling effect of $CaCO_3$ formation. Water absorption results showed a similar trend, with the accelerated carbonation samples displaying equal or lower values than the laboratory-conditioned ones. In contrast, the specific gravity of the samples was not noticeably affected by carbonation, suggesting that while the pore structure was altered, the overall bulk density remained unchanged.

3.2 Dynamic Modulus of Elasticity

Figure 4 displays the dynamic modulus of elasticity of all test mortars at ages of 28 days, 56 days (first batch) and 90 days (second batch).

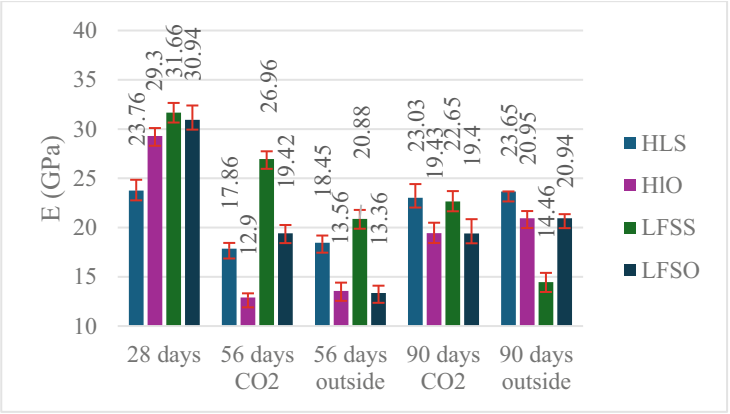


Fig. 4. Dynamic modulus of elasticity of samples at 28, 56 and 90 days.

The dynamic modulus of elasticity results showed notable variance across mixtures and ages. Both laboratory-conditioned and accelerated carbonation mortars exhibited significantly lower modulus at 56 days compared to the 28-day values, with the effect being especially pronounced for the olivine mixtures (over 60% reduction). This may be attributed to changes in curing conditions affecting proper hydration, as the samples were moved from the high-moisture curing chamber to the dry environments of the laboratory and the CO_2 chamber. At 90 days, modulus values partially recovered, with the hydrated lime mixtures showing slightly higher recovery than the LFS samples, indicating the slow progression of hydration and carbonation processes.

3.3 Compressive Strength

Figure 5 displays the compressive strength results of the test mortars at ages of 28 days, 56 days and 90 days.

The compressive strength results demonstrate a clear trend related to curing conditions and mixture composition. At 28 days, all mixtures exhibited relatively low mechanical strengths (approximately 2.0 to 5.5 MPa). At 56 days under accelerated carbonation, all mixtures showed a substantial increase in strength with LFSS reaching a maximum strength of 15.71 MPa. Compared to samples cured under laboratory conditions at 56 days, carbonation curing showed compressive strength increase of approximately 23.5% for HLS, 6% for HLO, 64% for LFSS, and 45.8% for LFSO. This is consistent with the findings of Liu et al. [14] which found that carbonation curing of cement-based mortars with 30% steel slag replacement showed compressive strength increase ranging from 12% to 64%. At 90 days, the strengths of carbonated samples remained significantly higher than those of laboratory-cured specimens for most mixtures, although they were slightly lower than the peak values observed at 56 days under high CO_2 curing, possibly due to the lower CO_2 concentration in the chamber during the accelerated carbonation of the second batch. Overall, mixtures containing LFS consistently exhibited higher strength values than the hydrated lime mixtures across all curing conditions. The

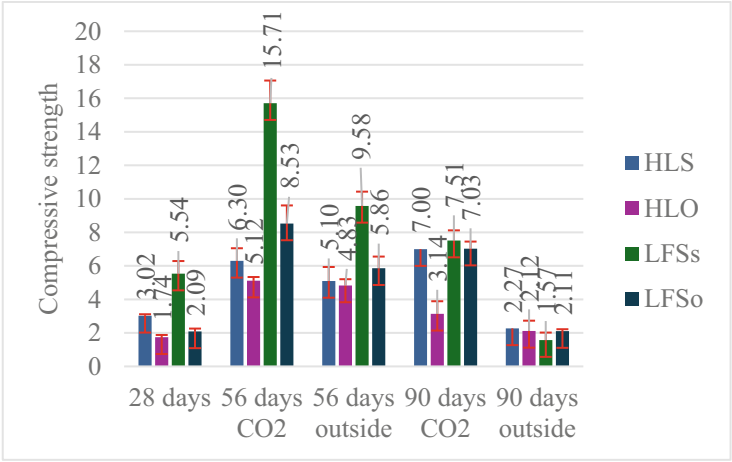


Fig. 5. Compressive strength of samples at 28, 56 and 90 days.

potentially high reactivity of LFS after carbonation has also been found by Zhang et al. [15].

3.4 Thermogravimetric Analysis

Figures 6 and 7 display the measured $Ca(OH)_2$ and $CaCO_3$ percentages respectively.

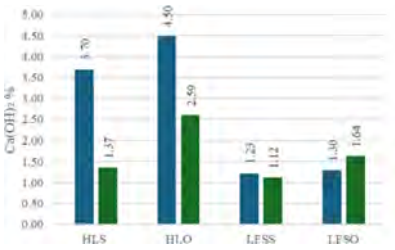


Fig. 6. $Ca(OH)_2$ content of samples at 90 days.

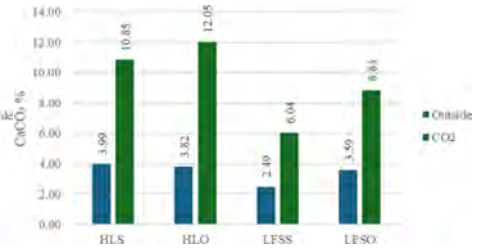


Fig. 7. $CaCO_3$ content of samples at 90 days.

Thermogravimetric analysis at 56 days showed distinct differences in $Ca(OH)_2$ content depending on the composition and curing conditions of the mixtures. Hydrated lime mixtures exhibited a pronounced reduction in $Ca(OH)_2$ under accelerated carbonation, decreasing by approximately 63% (HLS) and 42% (HLO), indicating consumption during the carbonation process. On the contrary, LFS mixtures showed minimal change (LFSS) or even slight increases (LFSO), showing that $Ca(OH)_2$ was less involved in the carbonation process or was even replenished through hydration.

$CaCO_3$ formation was noticeably higher in carbon chamber samples, with hydrated lime mixtures reaching 10.85% (HLS) and 12.05% (HLO), compared to 6.04% (LFSS)

and 8.83% (LFSO) for LFS mixtures. This change represents a 300% increase for hydrated lime mixtures and a 250% increase for LFS mixtures. Notably, the olivine mixtures exhibited higher $CaCO_3$ content compared to sand mixtures, indicating that olivine inclusion slightly contributes to carbonation.

3.5 Stereoscopic Observation

Stereoscopic images of the samples at 90 days are displayed at Fig. 8.

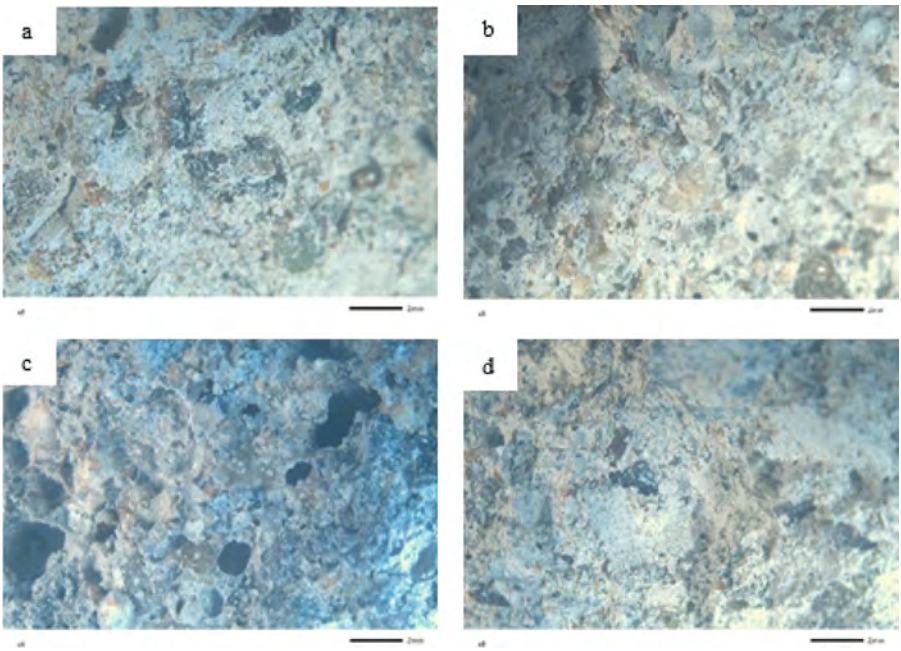


Fig. 8. Stereoscopic images of the mixtures: (a) HLS, (b) HLO, (c) LFSS, and (d) LFSO. (8×)

All samples, when observed under the stereoscope, exhibited a relatively loose and non-uniform matrix, with large pores and microcracking, which can be attributed to the low cement percentage and the use of alternative binders and aggregates. Additionally, both lime and LFS mixtures displayed noticeable color variation. Mortars containing hydrated lime were lighter shades, likely due to the formation of calcium carbonate on the surface, whereas LFS-based mixtures exhibited darker tones, due to the presence of minerals containing iron or other metals within the slag.

4 Conclusions

The results indicate that steel slag, LFS, and olivine can work well as substitutes in mortar production, even at very high replacement levels (55–80% in this study), without severely compromising physical and mechanical performance. This highlights the

potential of these non-conventional materials to significantly reduce reliance on traditional binders and aggregates. Maintaining the samples at a 40% CO_2 atmosphere increased carbonation levels significantly, particularly in mixtures containing hydrated lime. The type of aggregates also slightly influenced carbonation, with olivine increasing carbonation compared to river sand.

Additionally, carbonation increased the compressive strength in all mixtures, while samples with LFS instead of hydrated lime consistently showed better mechanical performance among the tested compositions. The results indicate that carbonation curing improves material performance while absorbing a large volume of industrial by-products. Overall, this approach offers a viable pathway for producing more sustainable mortars with reduced environmental impact through carbonation.

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Advancing Sustainable Construction: Wood Bio-Composite Panels with Embedded Phase Change Materials

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Abstract. Reducing energy demand in buildings is essential to mitigate greenhouse gas emissions. A proven strategy to achieve this is to enhance building thermal inertia through phase change materials (PCMs), which significantly lower energy consumption associated with heating and cooling. Current research trends are shifting towards solutions that combine energy efficiency with sustainability, prioritizing the reduction of environmental impact and alignment with circularity principles. This study presents the concept developed within the European co-funded BIOBUILD project (GA 101135629), which aims to produce wall and flooring systems for timber buildings using bio-composites. The proposed technology integrates bio-based PCMs into solid wood and natural fibers bonded with plant oil resins, lignin, and fungal mycelium, creating a cradle-to-cradle approach for sustainable construction. The concept will be validated in real buildings in Sweden and Spain. Preliminary thermal characterization results of these bio-composites are reported in this paper, comparing their thermal properties with those of conventional materials. Findings indicate promising thermal performance of the proposed solution, supporting the potential of BIOBUILD technology to reduce energy demand while promoting environmentally friendly building practices aligned with circular economy principles.

Keywords: Bio-composites · phase change materials · sustainable construction · thermal inertia · energy efficiency · circular economy

1 Introduction

The building sector remains a major contributor to global energy consumption and greenhouse gas emissions, underscoring the urgent need to move towards more sustainable, circular, and energy-efficient construction practices [1]. Improving the thermal performance of buildings is a key strategy for reducing energy demand, increasing efficiency, and minimizing the environmental impacts associated with the intensive use of heating and cooling systems [2].

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In this context, passive thermal energy storage (TES) systems have received increasing attention for their ability to mitigate indoor temperature fluctuations and reduce building energy consumption [3]. Among the various TES solutions, phase-change materials (PCMs) stand out for their high energy density and their capacity to store and release latent heat close to thermal comfort ranges [4, 5]. Their integration into building envelope elements allows for the shifting of energy demand peaks and improved thermal stability. However, their effectiveness depends largely on the thermophysical compatibility between the PCM and the substrate materials, as well as the quality of the incorporation process [6].

The construction industry is simultaneously moving towards models based on sustainability and circularity, driven by principles such as the cradle-to-cradle approach, which promotes the use of renewable, low-carbon, and easily recyclable or reusable materials [7]. Within this framework, wood and wood-based composites have emerged as particularly promising support matrices for PCMs due to their porosity, structural versatility, and biogenic origin [8–10]. Integrating PCMs into wood particles allows for the creation of multifunctional composites capable of combining insulating properties with latent heat storage capacity.

However, although the literature demonstrates its potential, studies that simultaneously analyze the effects of material composition, PCM content, and impregnation quality on key thermophysical properties, such as thermal conductivity [11], specific heat capacity (Cp), thermal transmittance (U-value), or thermal stability coefficient (TSC) remain limited. Likewise, research evaluating these materials in configurations representative of real-world construction applications, such as paving systems or interior wall panels, is scarce.

To address these challenges, the BIOBUILD project [12] has emerged as a key European initiative. Funded by Horizon Europe (GA 101135629), it aims to develop fully bio-based building materials with integrated thermal energy storage. The strategy incorporates bio-PCMs into wood- and fiber-based composites bonded with resins from plant oils, lignin, and fungal mycelium. This approach reduces reliance on fossil materials and related emissions, enhances the thermal inertia of the building envelope, lowers heating and cooling demand, and supports a more stable indoor environment.

This study falls within this context and focuses on the thermal characterization of composite samples developed within the BIOBUILD project. The study analyzes the thermophysical behavior of wood particle composites impregnated with PCM along with reference samples, with the aim of identifying optimal configurations for their application in building envelope elements. In this way, it contributes to advancing the development of sustainable, circular, and energy-efficient building materials, aligned with the current challenges of the sector.

2 Thermal Characterization of Materials

The study focused on evaluating wood-based composite panels incorporating bio-based binders along with PCMs, with the aim of enhancing their thermal performance without compromising their sustainability and biodegradability. For this purpose, various samples with binders of biological origin, obtained from vegetable oils, were studied, represented in Fig. 1.

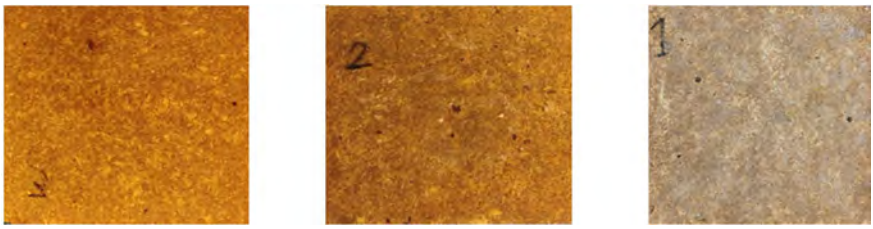


Fig. 1. Wood-based panels integrating bio-binders and PCM.

For each type of binder, two composite material variants were evaluated: reference samples and PCM-impregnated samples. In the case of the PCM-impregnated composites, the PCM was incorporated along with the wood fibers and the polymeric binder. The reference samples, on the other hand, were manufactured using the same combination of wood particles and binders, but without the addition of PCM.

Two reference samples and one PCM-impregnated sample were used in this study; their main characteristics, including dimensions and weight, are summarized in Table 1.

Table 1. Characteristics of the samples.

Sample type	Length (m)	Width (m)	Thickness (m)	Weight (kg)
Reference	0.193	0.190	0.020	0.496
PCM-impregnated	0.193	0.190	0.020	0.640

The thermal properties were determined using two characterization methods and devices. First, the experimental procedure described by de Gracia et al. [13] was applied using a homemade thermal behavior analyzer (Test box) developed at the University of Lleida. The sample was placed horizontally between two independently controlled compartments, while temperature and heat flux sensors on both surfaces recorded thermal evolution and transmitted heat. By using different temperature settings in the baths, the thermal behavior of the material under steady-state conditions, its heat storage capacity under uniform heating, and its dynamic response to daily temperature variations could be evaluated. Through this approach, experiments were carried out to evaluate the thermal conductivity, thermal transmittance (U-value), heat capacity, and dynamic thermal behavior of the samples. Regarding dynamic thermal behavior, two key indicators were analyzed. The thermal stability coefficient characterizes the attenuation of the temperature wave as it travels through the material from top to bottom, defined as the ratio between the temperature amplitudes at the bottom and top surfaces. In turn, the thermal lag describes the delay between the peak temperature on the exposed side (top surface) and the corresponding peak heat flux measured on the opposite surface (bottom surface).

On the other hand, the effective thermal conductivity of the wood composite was evaluated using a TPS 2200 Hot Disk equipment. The measurements of reference samples (without PCM) were carried out only at 21 °C, while in the samples impregnated with PCM they were carried out at different temperatures (10 °C, 21 °C, and 40 °C) to analyze

how this property evolves in the solid, liquid, and mushy phases of the PCM. To ensure reliability, each measurement was repeated three times, with the sensor placed between two polished samples to eliminate air gaps. Acting as both heat source and temperature detector, the sensor enabled thermal conductivity characterization under manufacturer-recommended power and duration settings [14], providing an accurate assessment of the composite thermal behavior under the imposed thermal regime.

The thermo-physical characterization carried out with the Test Box equipment revealed clear relationships between the composition of the materials and their capacity for heat transfer and storage in wood composites with vegetable oil binder, as shown in Table 2.

Table 2. Results of thermal characterization using Test Box equipment.

Sample type	Thermal conductivity (W/m·K)	Specific heat (kJ/kg·K)	Thermal stability coefficient (−)	Thermal lag (h)
Reference	0.11 ± 0.01	2.41 ± 0.23	0.58 ± 0.01	0.55 ± 0.01
PCM-impregnated	0.13	3.71	0.63	0.32

All samples exhibit low thermal conductivity (≈0.10–0.13 W/m·K), confirming their insulating character, although PCM incorporation caused a slight increase. Consequently, the thermal stability coefficient rose marginally, while thermal lag decreased from 0.55 h to 0.32 h. A key benefit of PCM integration is the substantial increase in specific heat capacity, from approximately 2.4 kJ/kg·K to 3.7 kJ/kg·K, reflecting the contribution of latent heat.

The results obtained using the Hot Disk equipment are shown in Table 3.

Table 3. Results of thermal characterization using Hot Disk equipment.

Sample type	Thermal conductivity (W/m·K)		
	@10 °C	@21 °C	@40 °C
Reference	–	0.12	–
	–	0.12	–
PCM-impregnated	0.18	0.19	0.18

Thermal conductivity results for the reference sample showed excellent agreement with Test Box measurements. However, the PCM-impregnated sample exhibited higher conductivity, likely due to the transient nature of the measurement technique. In addition, no significant temperature-dependent variations were observed.

3 Pilot Buildings for On-Site Demonstration of the Technology

The BIOBUILD technology will be validated in real buildings through two full-scale pilot houses located in distinct climate zones: a Mediterranean continental climate in Lleida (Spain) and a cold temperate climate in Uppsala (Sweden). This dual-site approach enables assessing the performance of the bio-based TES materials under contrasting environmental conditions, extending from hot-dry summers and cool winters in Spain to mild summers and cold winters in Sweden.

The experimental activities build on the extensive experience of the University of Lleida in evaluating passive TES solutions in real buildings. Over the past years, multiple testing campaigns were conducted on typical insulation materials and construction systems in its experimental facility located at Puigverd de Lleida, Spain [15, 16]. These previous studies provide a robust methodological basis for the assessment of novel bio-based materials under realistic operating conditions.

The implementation of the BIOBUILD concept will involve the integration of bio-based composite panels with PCM in one of the pilot houses, while the second will remain unaltered to serve as an experimental control. The effects of integrating the PCM-based materials will be assessed in terms of indoor thermal performance and energy demand through two complementary experimental strategies:

- Free-floating indoor temperature experiments

  This configuration allows the indoor temperature to evolve naturally without active conditioning, enabling the evaluation of the building thermal inertia and its ability to dampen temperature fluctuations. The focus is placed on quantifying thermal stability, daily temperature amplitude reduction, and time-lag effects influenced by the integration of BIOBUILD materials.
- Controlled-temperature experiments

  In this mode, indoor temperature is maintained within predefined setpoints using a heating or cooling system. The comparison of energy consumption with and without BIOBUILD materials allows quantifying the energy savings associated with their implementation. This methodology provides a direct assessment of the contribution of passive TES to reducing building energy consumption.

To illustrate the characteristics of the pilot buildings used for the demonstration, Fig. 3 presents exterior photographs of the test houses located in Lleida (Spain) and Uppsala (Sweden). These images provide an overview of the architectural context and the contrasting climatic environments in which the BIOBUILD technology will be assessed.

Complementarily, Fig. 2 shows interior views of the equipped dwelling, including different rooms where the bio-based panels with PCM will be installed. These images highlight the specific areas of integration and support the description of the experimental setup implemented inside the building.



(a) (b)

Fig. 2. Exterior views of the pilot houses in: (a) Lleida (Spain) and (b) Uppsala (Sweden).



Fig. 3. Interior views of wood-based panels integrating bio-binders and PCM.

4 Conclusions

The development of sustainable construction materials with enhanced thermal capacity represents a key strategy in the decarbonization of the building sector. Within this context, BIOBUILD technology proposes an innovative approach based on wood composites incorporating bio-based phase change materials, with the objective of reducing energy demand in buildings while maintaining circularity, low embodied carbon, and full recyclability. The material solutions developed in the project are intended for potential implementation in both residential and non-residential buildings across different European regions, thereby addressing a broad range of architectural and climatic conditions.

The extensive thermophysical characterization carried out in this study provides essential insights into the behavior of the BIOBUILD composites, helping to clarify their capacity for heat storage, thermal inertia, and heat transfer properties. These results contribute to a more comprehensive understanding of the technical potential of BIOBUILD materials to lower heating and cooling needs in buildings through passive thermal energy

storage mechanisms. The complementary evaluation of thermal conductivity, heat capacity, dynamic behavior, and performance under controlled and free-floating conditions builds a solid foundation for assessing their real-world applicability.

The next phase of the project involves full-scale demonstration in pilot houses located in Spain (Lleida) and Sweden (Uppsala). The experimental methodology designed for these buildings aims to evaluate the BIOBUILD technology under representative operating conditions, enabling the assessment of real energy savings, improvements in indoor thermal stability, and performance across contrasting European climates. By comparing the results obtained in the equipped dwelling with those of the reference building, the demonstration will allow quantifying the true benefits of integrating bio-based PCM composites into the building envelope.

Overall, the results of the material characterization combined with the forthcoming demonstrations in pilot buildings position the BIOBUILD technology as a promising solution for advancing the sustainability, energy efficiency, and climate resilience of future European building stock.

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Exploring Circularity Aspects in 3D-Printing Construction

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Abstract. The growing environmental challenges in the construction sector, such as resource depletion and waste management, emphasize the urgent need to integrate circular economy principles into the built environment making the transition from a linear to a circular construction model a necessity. 3D printing (3DP) technology, or also known as Additive Manufacturing (AM), is gaining ground in the construction sector, as it provides a completely new and extended freedom of shape, functionality, as well as materials and costs savings with efficiency. The research community has already recognized and evaluated the sustainability of this construction method, however, its investigation under the prism of circular economy (CE) remains limited, with only a few references and without a holistic approach. The objective of this study is to conduct a comprehensive examination of the circularity aspects of this method through literature analysis, to ultimately assess how and at what extend 3DP addresses CE principles. Furthermore, the study will extend to the combination of 3DP technologies with methods, such as prefabrication and topology optimization, to highlight further advantages, such as the reduction of required materials and minimized construction waste, while enabling the use of alternative materials. The present research presents also a case study of a topology optimized 3D printed wall element, demonstrating the method's potential to support the transition toward CE practices.

Keywords: 3D printing · Circular Economy · Circular Strategies · Topology Optimization

1 Introduction

There is a substantial body of literature examining the environmental impact of the construction industry, giving rise to concerns about its sustainability and the necessity to identify alternative construction methods. 3DP technology is gaining ground in this competitive sector, on the path to a sustainable future, thanks to the advantages it offers over traditional methods. There are several approaches of 3DP structures made of concrete, clay or even mortars with the equivalent mechanical properties of stone [1, 2]. Many

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studies have underscored the economic, environmental, and productivity benefits of 3D concrete printing (3DCP) over conventional methods such as cast-in-situ and precast technologies, including the minimization of waste, the reduction in labour requirements and the elimination of the necessity for formwork during the manufacturing process [3, 4]. According to Hossain et al., 3DP promises to reduce construction waste by 30–60%, labour costs by 50–80% and construction time by 50–70% [5]. At the same time, many studies explore the mechanical properties of 3DPC but very few its seismic performance, as current research focuses on isolated structural elements and the existing design codes do not yet address AM structures. In this context, Chortis et al. explored seismic performance of 3DCP walls using numerical modelling to assess their structural behavior under earthquake loading [6]. As referred by Mercimek et al., who investigated the structural performance of unreinforced prefabricated 3DCP walls, 3DP structures can be designed as either reinforced or unreinforced depending on performance needs [7]. While 3DP technology is a major focus thematic in research and industry, its integration with CE aspects is not yet fully integrated. Very limited works investigate 3DP under the prism of CE. Silvennoinen et al. used AI-assisted screening of literature and by using a coding scheme presented how 216 AM construction components integrate CE through the 10R framework. The findings show material reduction is the primary circularity strategy, and there is emerging potential for reuse and lifespan extension, while there is a gap in combining strategies and conducting comparative LCAs [8]. Another study explored the current literature to identify how the different R strategies affect the AM from the design phase, on the product level [9]. Gümrük et al. highlighted that the full life cycle of 3DCP is limited, and introduced 3DCP-CI, a framework to assess the circularity potential of 3DCP designs [10]. While existing studies explore material alternatives or design perspectives in 3DP, the field integration with circularity remains underdeveloped. This study outlines how these aspects, i.e. design considerations, material opportunities, environmental benefits and digital integration are currently addressed, highlights how they enable circularity, shows the remaining gaps and challenges and presents a case study that demonstrates how combining topology optimization with 3DP can support CE principles.

2 Materials and Methods

In this research, literature review was carried out using targeted databases, in particular Science Direct, Web of science and Google Scholar, using identified keywords such as"3D printing" OR "additive manufacturing" AND ("circular economy" OR circularity) AND (construction OR building OR "built environment" OR "civil engineering")) and also manual searching. This was followed by screening the sources to identify eligible literatures and finally selecting key documents for content analysis (32 in total) with the criterion of relevance to the paper's thematics. This paper is part of a larger study under development and some of its results are presented in a shortened form with an emphasis on the following thematics regarding their application in 3DP: design considerations, material opportunities, environmental benefits and digital integration. A scientometric analysis was also conducted using Science Direct database with specific criteria (98 results) and VOS viewer software [11], to create a term co-occurrence map based on text

data (title and abstract fields) from reference manager files with a minimum number of occurrences set at 5. From 3605 keywords, 101 meet the threshold and after removing generic terms they were visualized in 6 clusters. For the presented case study, finite element analysis and topology optimization methods were used.

3 Results

3.1 Scientometric Analysis

The scientometric analysis highlights the frequency of terms' occurrence and the interconnections among the targeted literature in order to map and present an overview of the current situation.

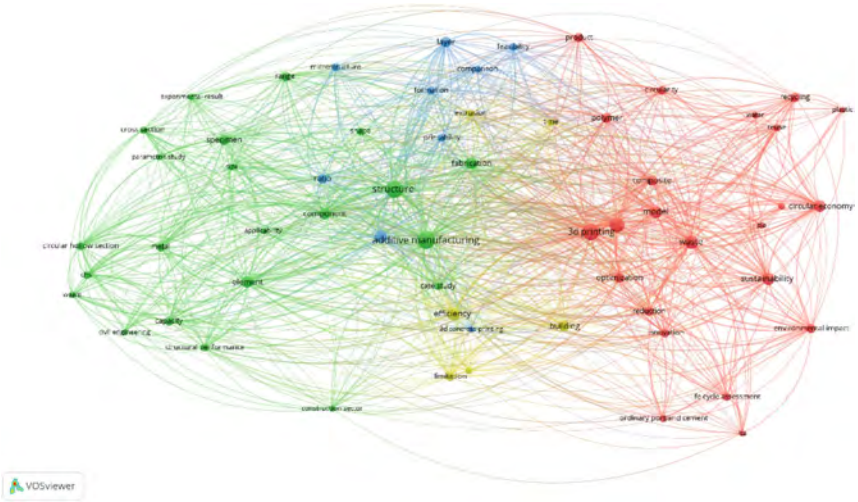


Fig. 1. Term co-occurrence map made with the VOS viewer software on the basis of the given bibliographic search.

The network visualization (Fig. 1) shows that, despite the targeted search combining 3DP and CE in construction, literature remains strongly dominated by technical and material-oriented research. The largest and most interconnected nodes relate to structural behavior, mechanical performance, and AM processes, indicating that the field has developed primarily around these aspects. In contrast, CE concepts form a smaller and less central cluster, and, although sustainability terms appear, they are not yet deeply integrated into the core research agenda. Most circularity related keywords connect to waste management and environmental impact, rather than to advanced circular strategies, such as reuse, design for disassembly, or closed-loop material cycles. This demonstrates a clear research gap: the integration of CE principles into 3DP construction is still emerging and remains underdeveloped, highlighting the need for future studies that bridge technical innovation with circularity aspects.

3.2 Literature Overview: Design Considerations

3DP design strategies considerations can converge on three CE interlinked aims: material efficiency and less requirements through form and geometry optimization, modularity and prefabrication for precise fabrication, and DfD to enable reuse and recycling. Some case studies in the literature illustrate how these aims are implemented and where practical constraints and challenges remain. A study presented a hybrid vaulted slab that combines digitally optimized printable modules with a novel joint system to enable DfD, reduce embodied carbon, and improve material recovery [12]. The paradigm of Striatus bridge demonstrates how modular assemblies with appropriate geometries and unreinforced masonry allow material to be placed only where compressive flows demand it. Also, by relying on frictional joints, they can both reduce embodied carbon and enable repair, reuse, and recycling principles [13]. Prefabrication in conjunction with 3DP technology increases fabrication precision, consistency, and speed, and can maximize material utilization while reducing waste [14, 15]. However, the literature refers to module size constraints printer build volumes, challenges related to large-scale construction projects and transport limits, which can shift environmental and economic trade-offs toward transportation emissions and handling costs [16–18]. This indicates that design strategies must be evaluated holistically, rather than focusing solely on material minimization. 3DP can also support circularity by enabling targeted rehabilitation of existing structures through add-on fabrication and repair, allowing damaged or outdated components to be restored or adapted for new uses rather than replaced [19].

3.3 Literature Overview: Material Opportunities

The progress of 3DP of structures is in line with the evolution of materials, as successful extrusion and gradual construction require mixtures with strictly controlled rheological and mechanical properties. In this context, concrete remains the dominant material known as 3DCP method, but its performance relies heavily on the use of specialized admixtures that regulate critical parameters such as thixotropy, setting time, early age strength, and material consistency during extrusion. Modern superplasticizers, viscosity-modifying agents, set-control additives, nanomaterials, and tailored fiber systems allow concrete to maintain flow during transport, while rapidly gaining the stiffness needed to support subsequent layers. Sharma et al. give a thorough analysis of the factors affecting the rheological behavior of cementitious mixtures [20]. At the same time, research is expanding beyond conventional cementitious systems, toward alternative binders and aggregates, such as geopolymers, calcined-clay blends, recycled mineral fractions, and bio-derived components that aim to reduce the environmental impact and introduce new functional characteristics [21]. A recent work demonstrates that reducing cement through recycled materials, such as porcelain polishing residues, can enhance sustainability without compromising printability [22]. Also, earth-based AM using locally sourced, recyclable soil and on-site robotic fabrication can reduce emissions, while enabling complex forms, representing a circular construction approach with a low-impact processing [23]. However, there may be some challenges including the lack of standardized testing methods for printable materials and material sensitivity as small variations in composition can significantly affect flow and interlayer bonding [24, 25]. This highlights the need

for coordinated research to meet performance and sustainability goals, while remaining under the prism of CE.

3.4 Literature Overview: Environmental Benefits

Unlike conventional construction methods, which generate substantial waste, 3DP offers precise material deposition, significantly reducing waste. The majority of environmental impact assessment methodologies for AM are based on the Life Cycle Assessment (LCA) framework. According to Weng et al., who presented a comparative study of prefabricated 3DCP bathrooms versus the conventional method, the results indicated 25.4% reduction in cost, 85.9% reduction in CO_2 emissions and 87% less energy consumption, resulting in a 26% reduction in weight and 48% increase in productivity [3]. Another study refers that 3DP can reduce material waste by up to 60% [26]. Saad et al. described how LCA has been applied to 3DP and highlighted that material intensity remains the dominant factor, contributing considerably to the global warming potential (GWP) of construction systems [27]. A study demonstrated that the LCA cradle-to-gate for 3DP walls shows significantly lower impacts compared to conventional walls, with GWP at 608.55 kg CO_2 eq for 3DP versus 1154.20 kg CO_2 eq for traditional methods [28]. Hoschke et al. combined predictive LCA with topology optimization, enabling automated evaluation of multiple design criteria and highlighted how this approach reduces environmental impacts through lighter designs and optimized construction orientation that minimizes supports and material use [29]. It can be perceived that by optimizing construction, material reductions of up to 50% can be achieved [30].

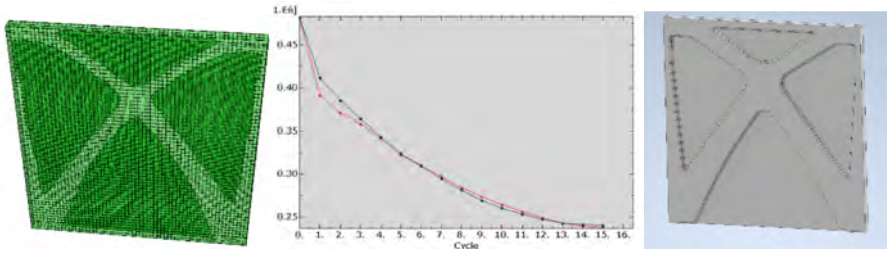
3.5 Literature Overview: Digital Integration

Digital integration can play a pivotal role in strengthening circularity within 3DP construction by enabling real time material tracking, lifecycle transparency, and data driven resource optimization. Linking 3DP with digital workflows improves its effectiveness, as BIM and parametric modeling integrate directly into printing processes, allowing accurate material estimation and optimized design [31]. In the same scope, digital optimization and modular prefabrication enable repeatable, high precision components that shorten schedules and minimize on site disruption [14]. Digital workflows can support coordinated design across architectural, structural, and MEP systems, as shown in a modular 3DPC residence case study [16].

4 Case Study

In the presented case study, a load-bearing wall 3 m wide, 3 m high and 0.15 m thick, was selected as a representative part of the overall structure. The applied loads were derived from the global structural analysis of the building [6] which was performed in accordance with the relevant Eurocode provisions. In order to achieve an accurate numerical representation of the structural response and capture potential failure mechanisms, the analysis was performed using the Concrete Damage Plasticity (CDP) model. The material selected for the analysis was cement mortar with a compressive strength of

20 MPa, a tensile strength of 7 MPa, and a density of 2.2 t/m^3. Within the CDP model, the compressive behaviour was defined according to the concrete compressive strength, while the tensile and shear behaviour were assigned based on the interlayer strength. This approach accounts for the layered nature of the printed structure, as described in [6, 32]. Topology optimization process was employed to ascertain the optimal printable wall geometry under the imposed loading and geometric constraints. Material removal was restricted to the inner region of the wall, while preserving a minimum thickness at both exterior faces. The objective of the optimization process was to minimize strain energy and material volume, with a target of achieving a 60% reduction in volume without compromising structural performance. The results are illustrated in Fig. 2a, where the darker regions indicate material removal. A 60% volume reduction is achieved in 15 optimization cycles (Fig. 2b). The geometry was extracted and redesigned to obtain a more constructible form (Fig. 2c).



a. b. c.

Fig. 2. a. Optimized geometry, b. Reduction in volume graph, and c. Section of final optimized geometry of the examined 3DP wall.

As presented in [33], a cradle to gate LCA analysis of the topology optimized wall element showed 53% reduction in CO_2eq-GWP and 58% less total primary energy compared to a conventional wall. This case study supports the integration of CE principles by reducing material use, minimizing waste at the design stage, and optimizing resource efficiency. By removing unnecessary material while maintaining performance, the approach directly promotes circularity. As this is ongoing research, it can be combined with the use of alternative materials and enable DfD principles through prefabrication, modularity and mechanical connections in the next steps. Future directions include material and wall specimen testing.

5 Conclusions

This research examined 3DP alignment with CE strategies through design approaches, material opportunities, environmental benefits, digital integration, and highlighted emerging challenges in each category. The scientometric analysis showed that the field offers substantial space for further exploration. The case study demonstrated a 60% reduction in volume through the integration of 3DP and topological optimization, illustrating the potential of CE strategies, especially regarding material reduction and waste

minimization, showing how these methods can provide circular and sustainable practices in the built environment.

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Mycelium and Coconut Fiber Composites: Analysis of the Manufacturing Process

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Abstract. The search for sustainable, low-environmental-impact materials has driven research into mycelium-based biocomposites, valued for their biodegradability, low energy demand, and potential application in civil construction. The performance of these materials depends directly on the composition of the substrate used during fungal growth. This study represents an initial investigative stage, with the objective of analyzing mycelial development across different substrate compositions, verifying the mycelium's ability to colonize the base material and form cohesive, rigid structures. The research is situated within a broader context, whose horizon is the development of biocomposite panels for application as cladding and sealing elements, with potential thermal and acoustic performance. The methodology involved the preparation of two sample groups with different substrate formulations, combining coconut fiber, sugarcane bagasse, and organic materials, subjected to sterilization, inoculation with fungal culture, incubation, molding, and drying processes. Evaluation was based exclusively on comparative visual analysis, considering criteria such as degree of mycelial colonization, growth homogeneity, and structural cohesion, which constitutes a methodological limitation of this phase. Results indicated that substrates containing sugarcane bagasse and cardboard favored greater colonization and better structural consolidation, while isolated coconut fiber exhibited limited internal development. It was concluded that substrate composition is a determining factor in biocomposite formation, and the next stages of the research plan for thermal and acoustic performance testing of the produced samples.

Keywords: Mycelium · Coconut fiber · Biocomposites · Agro-industrial waste · Biofabrication

1 Introduction

The civil construction sector is associated with high environmental impacts, including intensive consumption of non-renewable natural resources, high energy expenditure, and large waste generation. It is worth noting that construction activities cause direct and indirect environmental changes, such as deforestation, habitat degradation, biodiversity loss, and the compromising of ecosystem services essential to human survival [1–3].

Given this scenario, sustainability has become a fundamental paradigm for the sector, seeking to balance economic development with environmental preservation and the guarantee of resources for future generations [1]. In this context, sustainable materials such as

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biocomposites are developed from biologically sourced raw materials and present lower environmental impact. These materials can be defined as composites formed by biopolymers or bio-based polymers reinforced with natural fibers, representing a promising alternative for sustainable civil construction [4, 5].

This research aimed to analyze mycelial development across different substrate compositions, investigating the mycelium's ability to colonize the base material and form cohesive, self-supporting structures. To this end, the influence of substrate composition was evaluated, with emphasis on coconut fiber and sugarcane bagasse as agro-industrial reinforcement residues, on fungal growth and the structural consolidation of the produced biocomposites. The study represents an initial stage of a broader investigative process, whose horizon is the development of biocomposite panels or blocks intended for the cladding and sealing of spaces, with potential thermal and acoustic performance.

2 Literature Review

The development of sustainable materials has become essential in light of the environmental impacts generated by traditional production methods [6]. The growing concern with waste reduction, the consumption of non-renewable resources and carbon emissions has driven the search for alternatives that reconcile functional performance and environmental responsibility, principles that underpin the transition to a circular economy [7]. In this context, mycelium-based biocomposites have gained prominence in recent decades as an ecologically correct alternative to synthetic composites derived from non-renewable resources, such as oil and natural gas [8].

Biocomposites present great potential for the utilization of biological waste, such as husks, fibers and stems, which contributes to the principles of the circular economy. The use of fungi as biomaterials began in the 1990s, with studies focused on the production of paper and construction materials from mycelium, broadening the development of environmentally responsible alternatives [5]. Mycelium is the vegetative part of the fungus with advantages over synthetic polymers: low density, lower cost, lower energy consumption in the production process and the possibility of customizing physical properties, including mechanical resistance and thermal and acoustic insulation, according to the type of substrate and processing techniques used [6, 8, 9].

Species of the genus Pleurotus, mainly Pleurotus Ostreatus (Oyster Mushroom), have rapid growth and greater resistance to contamination, being considered renewable, safe, biodegradable and environmentally sustainable [6]. Studies have demonstrated the viability of producing non-cementitious construction materials from organic waste, using mycelium as a natural binder, noting that substrates such as sugarcane bagasse, sawdust and coffee husk present different performance levels in the quality of the blocks produced [10].

These fungi have a high capacity for lignin degradation and colonization of lignocellulosic materials, which favors their application in the reuse of waste from the agricultural, forestry and food industries, in addition to having economic, ecological and medicinal relevance [11].

These materials are formed mainly by cellulose and lignin, in addition to small quantities of extractives and mineral salts. Lignin is a complex natural polymer responsible

for the strength and rigidity of plant cell walls, found mainly in wood and bark. The speed of this decomposition process varies according to environmental factors, such as temperature, humidity and fungal diversity, resulting in the gradual conversion of organic matter into carbon dioxide and water, closing the carbon cycle that began in photosynthesis [12].

In the field of composite technology, the choice of matrix (in this case, mycelium) allows the incorporation of materials with a structural reinforcement function, enhancing mechanical properties, or with a filler function, reducing the cost and weight of the final material. Natural fibers, generally of plant or animal origin, are widely used as recyclable, low-cost fillers, although they present mechanical properties inferior to synthetic fibers [13]. Studies [4] have noted that natural fibers present variability in their physical and chemical properties, influenced by factors such as cultivation type, soil conditions, climate, fiber location in the plant and harvest period, which can impact the performance of the composites produced.

Studies [14] have demonstrated that culture media prepared with coconut and sugarcane waste present potential for mycelial development, with fiber treatment and hydration directly influencing the dispersion of the lignocellulosic material and, consequently, the efficiency of fungal growth.

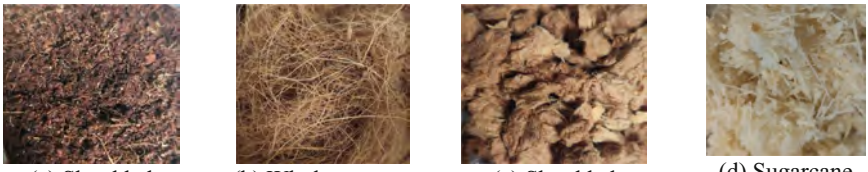
3 Materials and Methods

The research focused especially on the choice of substrate type and the influence of fiber size, providing a broader understanding of the complex interaction between substrate properties and mycelial development. Being divided into two stages: 1 – Selection of the mycelium; and 2 – Substrate preparation and cultivation.

3.1 Stage 1: Selection of the Fungus and Substrate (Selection of Materials)

The fungus Pleurotus Ostreatus was chosen as the matrix, as it is an available, non-pathogenic and edible fungal strain. The material was acquired already inoculated and cultivated on sorghum and wheat grain to accelerate the growth process. The primary substrate used as structural reinforcement was coconut fiber, obtained processed and ready for use in whole and shredded form. The shredded fiber was used in greater proportion due to its higher concentration of organic matter, the whole fiber was used in smaller quantities due to its large volume and low density.

For substrate supplementation, samples were prepared with the addition of cardboard and sugarcane bagasse. These materials are lignocellulosic, which means they provide the lignin and cellulose to feed the fungi [15]. The sugarcane bagasse and cardboard were processed in the laboratory. The cardboard represents a local and accessible waste material and was sorted so as to exclude parts that contained ink or any type of adhesive, then cut into small pieces and boiled in water for 1 h to remove impurities. The sugarcane bagasse and the cardboard were shredded in water and mixed with the coconut fiber, shredded in aqueous solution, to provide a more homogeneous mixture. After homogenization of the material, the water was drained and the substrate dried at ambient temperature (approximately 24° to 30 °C) for 72 h (Fig. 1).



(a) Shredded coconut fiber (b) Whole coconut fiber (c) Shredded cardboard (d) Sugarcane bagasse

Fig. 1. Images of the materials used in the substrate.

3.2 Stage 2: Sample Preparation and Cultivation

Twelve samples of 200 g each were produced, divided into 2 groups: 1 – higher moisture and 20% mycelium; 2 – lower moisture, more nutrients and 25% mycelium [9] (Table 1). Samples produced solely with whole coconut fiber had a reduced weight due to its large volume and low density.

Table 1. Sample groups.

Group 1	
SAMPLE 01	160 g shredded coconut fiber +40 g mycelium
SAMPLE 02	20 g whole coconut fiber +40 g mycelium
SAMPLE 03	155 g shredded coconut fiber +5 g whole coconut fiber +40 g mycelium
SAMPLE 04	130 g shredded coconut fiber +30 g shredded cardboard +40 g mycelium
SAMPLE 05	20 g whole coconut fiber +30 g shredded cardboard +40 g mycelium
SAMPLE 06	125 g shredded coconut fiber +5 g whole coconut fiber +30 g shredded cardboard +40 g mycelium
Group 2	
SAMPLE 01	150 g shredded coconut fiber +50 g mycelium
SAMPLE 02	145 g shredded coconut fiber +5 g whole coconut fiber +50 g mycelium
SAMPLE 03	130 g shredded coconut fiber +20 g sugarcane bagasse +50 g mycelium
SAMPLE 04	125 g shredded coconut fiber +5 g whole coconut fiber +20 g sugarcane bagasse +50 g mycelium
SAMPLE 05	110 g shredded coconut fiber +10 g sugarcane bagasse +30 g shredded cardboard +50 g mycelium
SAMPLE 06	105 g shredded coconut fiber +5 g whole coconut fiber +10 g sugarcane bagasse +30 g shredded cardboard +50 g mycelium

Whole coconut fiber and sugarcane bagasse presented large volume and low density, having their proportions different from the normal samples. In Group 1 a 5% water

addition was made; in Group 2 only the moisture generated by the autoclave was maintained. The difference in moisture and nutrients aims to analyze the possible conditions of mycelial development.

The substrate was prepared and weighed on an analytical balance, mixed and placed in autoclavable plastic bags with air filters and sterilized at 121 °C for 30 min [16, 17]. After cooling, the mycelium was added, already inoculated, between 24 and 32 °C. Studies have demonstrated that mycelial growth occurs in different thermal ranges, however it presents more efficient performance at temperatures close to 28 °C, followed by 32 °C and 24 °C [11].

4 Results and Discussion

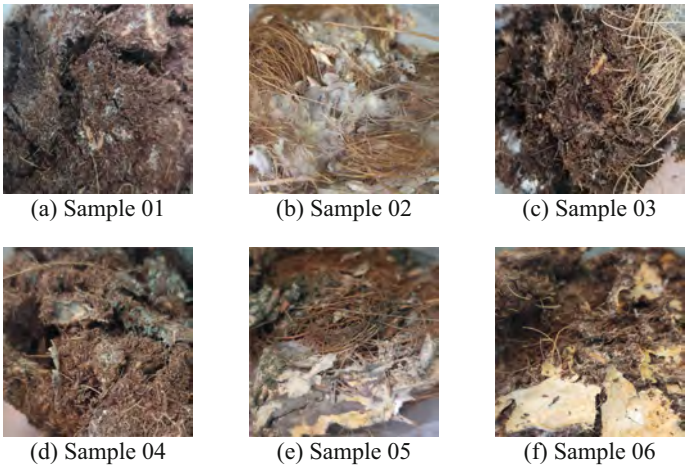
The evaluation of the samples was conducted through comparative visual analysis, considering criteria such as mycelial growth, density of the mycelial network formed and the capacity for self-structuring of the composite. It is important to highlight that this work represents an initial investigative stage, whose central objective is to analyze mycelial development in different substrate compositions, verifying the capacity of the mycelium to colonize and "dominate" the base material, forming a more cohesive and rigid structure. This preliminary phase constituted the beginning for the future development of biocomposite panels or blocks intended for the cladding and sealing of spaces, with potential thermal and acoustic performance.

The evaluated parameters made it possible to analyze the performance of mycelium in the colonization of the different substrates employed, as well as to understand how this colonization influenced the formation, cohesion and structural stability of the biocomposites produced.

The samples in this group (Fig. 2) presented lower mycelial development when compared to the others. Visually, limited mycelial growth and low binding density between the substrate particles were observed, resulting in composites with poorly consolidated structure. This behavior may be associated with excess moisture in the samples, which impairs substrate oxygenation and hinders adequate mycelial development. The low nutrient availability in the material used may have limited the growth of the organism, reducing its colonization capacity and its ability to form a denser mycelial network, a condition essential for the structural consolidation of the composite. Some samples were contaminated with different genera of mold, which prevented mycelial growth and made it necessary to discard the components.

The Group 2 samples (Fig. 3) presented more evident mycelial development. Greater colonization of the substrate was observed, with the formation of a more homogeneous mycelial network and better binding between particles, contributing to a more stable biocomposite structure. This behavior may be related to the addition of sugarcane bagasse, a material with greater nutrient availability and lignocellulosic composition favorable to mycelial growth. The presence of this agro-industrial residue appears to have stimulated fungal metabolism and favored the expansion of the mycelial network, resulting in better structural performance of the samples.

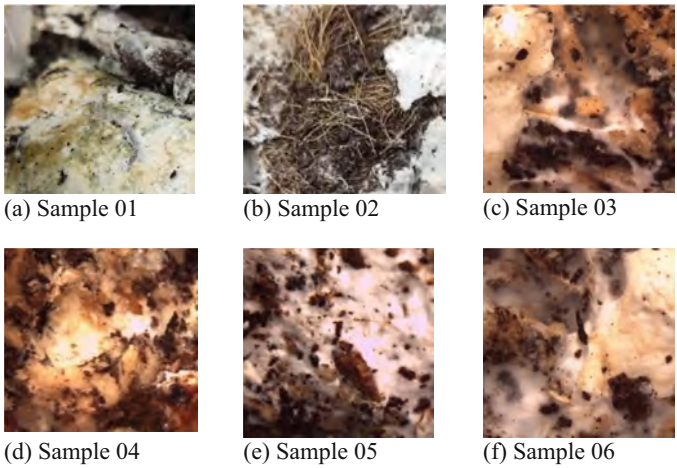
However, samples composed exclusively of coconut fiber did not present significant internal mycelial development. Although it was possible to identify surface growth in



(a) Sample 01 (b) Sample 02 (c) Sample 03

(d) Sample 04 (e) Sample 05 (f) Sample 06

Fig. 2. Images of each sample cultivated in Group 1.



(a) Sample 01 (b) Sample 02 (c) Sample 03

(d) Sample 04 (e) Sample 05 (f) Sample 06

Fig. 3. Images of each sample cultivated in Group 2.

some cases, colonization within the material was limited. This result may be associated with the physical characteristics of coconut fiber, its higher density and more compact structure, which hinder the penetration of mycelium into the substrate, in addition to its chemical composition presenting lower availability of readily assimilable nutrients.

In general, the results indicate that substrate composition exerts a direct influence on mycelial growth and biocomposite formation. The presence of materials rich in cellulose and nutrients, such as sugarcane bagasse and cardboard, proved to be a determining factor in promoting greater colonization and better structural consolidation of the samples. The cellulose present in the cardboard, associated with the lignocellulosic composition of the sugarcane bagasse, created favorable conditions for fungal metabolism, stimulating

the expansion of the mycelial network and contributing to the formation of a denser and more cohesive structure. This substrate combination demonstrates the potential of using agro-industrial waste and recyclable materials as a basis for the development of structured biocomposites.

5 Conclusion

The comparative visual analysis of the samples demonstrated that substrate composition and moisture conditions directly influence mycelial development and the structural formation of biocomposites. Group 1 samples presented limited growth and low structural consolidation. Group 2 samples demonstrated better mycelial colonization and greater self-structuring capacity, a result attributed to the presence of sugarcane bagasse in the substrate. Samples with isolated coconut fiber presented reduced internal development, indicating that this material, when used without combination with other substrates, may not favor the formation of structured mycelial composites.

These results reinforce the importance of the proper selection and combination of substrates in the development of mycelium-based biocomposites, highlighting the potential of agro-industrial residues such as sugarcane bagasse to improve the structural performance of these materials.

It is worth noting that the present study is based exclusively on qualitative visual observations, inherent to this research phase, without the performance of mechanical or instrumental tests. The subjectivity of visual analysis, the variability of cultivation conditions and the small sample size are factors that must be considered in the interpretation of the results, however they are important for initial decisions at the beginning of the research. Even so, this initial stage fulfills its objective by demonstrating the viability of mycelial growth in different substrates and identifying the compositions with the greatest potential for the development of structured biocomposites.

As a natural extension of this investigation, the next research stages plan for the production of panels or blocks at an enlarged scale, followed by thermal and acoustic performance testing. The objective will be the applicability of these materials as cladding and sealing elements in buildings, contributing to the development of sustainable construction solutions from agro-industrial waste and materials of biological origin.

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Thermal Activation of PLA/TPU Shape Memory Composites for Passive Solar Tracking

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Abstract. This research addresses the global challenge of energy efficiency in the built environment by proposing a transition from static to adaptive systems. The authors investigated 4D printing of Shape Memory Polymers (SMPs) to conceptualize a passive-solar-tracking system. This research first characterized the thermo-mechanical behavior of various polylactic acid (PLA) and thermoplastic polyurethane (TPU) blends. The experimental results showed that the 80/20 PLA/TPU composite achieved an optimal balance between shape fixity (91.5%) and recovery (91.9%), essential for reliable passive actuation. Based on the metamaterial's behavior, the authors proposed a single-axis passive hinge, creating a system that uses thermal conversion to generate motion and drive a sun-tracker coupled with a 5v photovoltaic panel toward its permanent shape during peak solar irradiance, achieving tracking errors as low as 2°. Combined with a gravity-bias mechanism for nocturnal reset, this framework demonstrated that SMP hinges can, in principle, match the efficiency of active trackers without the need for electromechanical sensors or external energy inputs, offering a sustainable option for renewable energy harvesting.

Keywords: 4D Printing · Smart Materials · Thermal Actuation

1 Introduction

The International Energy Agency (IEA) projects that global energy efficiency will improve by 1.8% in 2025, up from approximately 1% in 2024 [1]. However, this rate remains below the target set at COP28, which calls for a 4% annual improvement by 2030 to reduce climate impacts. Such inefficiency stems largely from the building sector, which accounts for 30% to 40% of global energy consumption [2].

Traditional architectural practices worsen these challenges by relying on static design strategies. To address this systemic failure, the industry must redefine building components as adaptive systems. While the efficiency of energy-harvesting systems often depends on their ability to adjust to solar geometry, the current literature frequently overlooks the limitations of passive, electronics-free mechanisms [2].

While active solar trackers increase energy yields by 20% to 45%, they rely on electromechanical actuators and sensors that increase embodied energy. Consequently,

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contemporary materials science promotes a shift toward smart systems that exhibit autonomous motion through structural responses to environmental stimuli [2]. Four-dimensional (4D) printing introduces time as a fourth dimension to additive manufacturing, enabling the fabrication of components with intrinsic shape-memory properties. Shape Memory Polymers (SMPs) are the primary material class for thermal activation, as they retain a trained, deformed state and return to a permanent shape upon heating above their glass transition temperature [3].

Material smartness enables the creation of self-regulating structures that respond to temperature fluctuations without external power, thereby reducing embodied energy and simplifying material recovery [4]. Polylactic acid (PLA) and thermoplastic polyurethane (TPU) blends are the most common composites for these applications; PLA provides structural rigidity and thermal responsiveness, while TPU provides elasticity for repeated actuation [5]. However, a significant gap remains in achieving two-way motion, which demands further studies on the subject.

This study focused on determining the thermomechanical properties and the shape-memory effect of various PLA/TPU blends to conceptualize and evaluate a single-axis passive sun-tracker that uses an SMP hinge to pan and tilt the photovoltaic panel.

2 Materials and Methods

This research has three primary methodological stages. The first one addresses the 3D fabrication of thermo-responsive composites. The second stage details their thermoforming programming and evaluates shape fixity and recovery. The final stage conceptualizes a passive sun tracker and assesses its potential energy efficiency.

This study used PLA as the active actuator and TPU as the compliant constraint layer. The authors modelled a 90 × 15 × 4 mm prism, later used to print the test coupons. The coupon complies with ASTM D790 [6], which specifies a minimum span-to-depth ratio of 16:1 for flexural testing. The authors produced 9 coupons with PLA/TPU weight ratios ranging from 10/90 to 90/10 with 10% increments. They used a 90° rectilinear infill at 20% density to approximate quasi-isotropic stiffness [3]. Additional print settings included 3 solid layers at the top and bottom, a wall count of 3, and a layer height of 0.1 mm. PLA was always in contact with the printing sheet, extruded at 220 °C and 70 mm/s, while TPU occupied the top layers, printed at 240 °C and 30 mm/s.

To induce the temporary shape, the authors used wet-heating programming (Fig. 1a). They immersed the coupons in a water bath at 100 °C for 2 min. This temperature is slightly above the glass transition temperature (T_g) of PLA (65–70 °C).

Following the first heating phase, the authors deformed the specimens into an L-shape using a clamp (Fig. 1b). To freeze the temporary deformation, they immersed the coupons in a cold-water bath for 10 s. Subsequently, they recorded the fixed angle after cooling (Fig. 1c). After fixation, the authors evaluated the Shape Memory Effect (SME) using a measurement rig (Fig. 1c, d) that secures the specimen in a cantilever configuration, aligning the deformation with a protractor behind the sample.

They calculated the Shape Fixity Ratio (FR_f) to quantify the material's ability to retain the programmed shape. After cooling, the authors measured the fixed angle (θ_f) upon removing the constraint. The FR_f value was determined using Eq. (1) [7, 8]. After

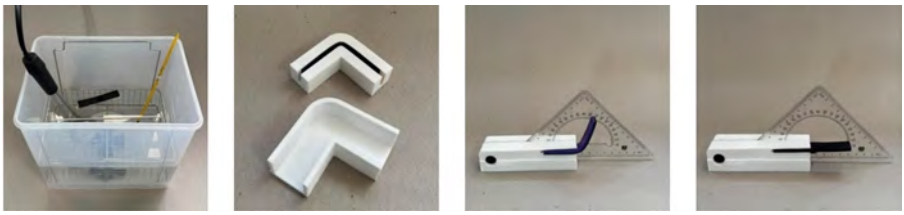


Fig. 1. (a) hot-water bath; (b) clamping; (c) fixed angle after cooling; (d) final shape recovery.

calculating the FR_f, the authors reheated the specimens above T_g to trigger shape recovery. To quantify the effectiveness of shape memory and the final recovered angle (θ_r), they used the Shape Recovery Percentage (RP_r) shown in Eq. (2).

$$FR_f(\%) = \frac{\theta_f}{\theta_p} \bullet 100 \tag{1}$$

$$RP_r = \left(\frac{\theta_f - \theta_p}{\theta_f}\right) \bullet 100 \tag{2}$$

This study used analytical modeling to evaluate the SMP's potential for solar tracking without immediate field deployment. From this step onward, the coupons act as responsive hinges, varying from θ_f to θ_r. The authors simulated the hinges' motion by mapping the shape-recovery profile to the Sun's position (α_{sun}). They estimated their angular position, $\alpha_{tracker}$, using Eq. (3), and their specific displacement at each predicted time and temperature ($RP_r(T)(t)$). They subsequently calculated the Tracking Error (E_{track}) to quantify the kinematic precision throughout the East-to-West cycle (Eq. 4).

$$\alpha_{tracker}(t) = \theta_f \bullet [1 - RP_r(T)(t)] \tag{3}$$

$$E_{track} = |\alpha_{sun} - \alpha_{tracker}| \tag{4}$$

To evaluate the impact of E_{track} on power generation, the authors applied the cosine law of illumination, which describes the reduction in radiation at a misaligned surface. They estimated the Potential Energy Efficiency (η_{energy}) using Eq. (5) over the entire diurnal cycle (7:00 to 16:00) of the spring equinox (21 March) and compared η_{energy} of the tracking system to a static reference PV panel oriented at a fixed North-facing angle.

$$\eta_{energy} = \cos(E_{track}) \tag{5}$$

3 Results

Normally, SMP component fabrication adopts fused-deposition machines with multiple nozzles to extrude different materials simultaneously. However, the *PrusaMINI+*, which was adopted in this study, has only one nozzle, requiring a manual filament swap halfway through the process. To address this, the authors developed a custom *G-code*

that includes an *M600* command to automatically initiate the filament change procedure, move the printhead away from the print, and purge the remaining filament from the hotend heatbreak. For instance, the command line uses the following syntax: *M600 [B < beeps>] [E < pos>] [R < temp>] [X < pos>] [Y < pos>] [Z < pos>]*. Here, *[B]* sets the number of buzzer alerts so the user knows when to swap the filament, *[E]* controls pausing, parking, and filament retraction, *[R]* adjusts the nozzle temperature, and *[X], [Y],* and *[Z]* define the coordinates for the custom pause. The parameters *[B], [E],* and *[R]* remained the same for all printed coupons, with *[R]* programmed to increase the nozzle temperature from 220 °C to 240 °C before the filament change from PLA to TPU. This custom *G-code* could help other researchers develop multi-material components using low-cost fused deposition machines.

In the first test-prints, the halfway manual filament change caused a drop in PLA's surface temperature, impairing TPU adhesion. The initial delamination possibly occurred due to the *PrusaMINI+* open-frame configuration. The authors corrected the temperature drop by placing the machine inside a heated box, maintained at around 45 °C. Moreover, the 20 °C increase in nozzle temperature introduced by the *M600* command improved interlayer diffusion, promoting stronger material bonding.

The authors evaluated the mechanical trade-off between the structural rigidity of PLA and the elastomeric resilience of TPU by analyzing Shape Fixity (FR_f) and Shape Recovery (RP_r) (Table 1). The experimental results indicate that the 70/30 PLA/TPU composite achieved the highest FR_f value of 94.4%, effectively retaining the programmed 90° angle with minimal elastic deformation upon cooling (Table 1). However, the inherent stiffness of this specific blend restricted the RP_r to 87.8%, resulting in a residual angle of 10.3° following full thermal activation.

Table 1. Shape Fixity Ratio and Recovery of all analysis coupons.

Coupon		Shape Fixity Ratio			Shape Recovery Ratio		
PLA (%)	TPU (%)	θ_p (°)	θ_f (°)	FR_f (%)	θ_f (°)	θ_r (°)	RP_r (%)
90	10	90	84.0	93.3	84.0	12.0	85.7
80	20		82.3	91.5	82.3	6.7	91.9
70	30		85.0	94.4	85.0	10.3	87.8
60	40		82.7	91.9	82.7	15.7	81.0
50	50		82.7	91.9	82.7	15.7	81.0
40	60		80.3	89.3	80.3	9.7	88.0
30	70		73.0	81.1	73.0	7.7	89.5
20	80		70.3	78.1	70.3	6.3	91.0
10	90		63.7	70.7	63.7	5.0	92.1

For instance, increasing the TPU ratio enhanced the specimens' kinematic recovery while proportionally diminishing structural fixity. The 10/90 PLA/TPU composite demonstrated superior RP_r, returning almost entirely to the original flat state with a

residual angle of only 5°, despite a significant reduction in FR_f. These findings suggest a direct correlation between the soft-segment concentration and the polymer network's ability to release stored entropic energy. The 80/20 PLA/TPU blend provided a balanced performance, exhibiting an FR_f of 91.5% and an RP_r of 91.9%, with a minimal residual angle of 6.7°. For repetitive applications, the authors emphasize the need to prioritize this equilibrium, ensuring that the kinetic components maintain sufficient flexibility to achieve full actuation under solar-thermal stimulation.

Acknowledging the capacity of all test coupons to bend and recover their initial position, the authors considered that all blends could be used as responsive actuators. Therefore, the idea for the tracker is to place the 90°-bent coupons on a wedge base with two 45°-sloped surfaces, one facing east and the other facing west. The PV panel would attach to the east-facing half of the coupon. As the SMP hinges reach higher temperatures (late morning), they would return to a flat position, forcing the PV panel to face west. The tracking mechanism is shown in Fig. 2 a–d in section 4.4

Before prototyping the system, the authors employed analytical modeling to predict its operational dynamics. This approach simulates the system's behavior by treating each coupon as an SMP hinge, without constructing various prototypes or taking extensive physical measurements across multiple experimental scenarios. Thus, the authors calculated the hinges' surface temperatures, determined their bending based on temperature gains, tracked the errors, and estimated potential energy generation.

To characterize the thermal and mechanical behavior of polymers under solar exposure, the authors selected the spring equinox as a representative date. They extracted hourly solar altitudes, direct normal irradiance (SI), and outdoor air temperature (T_{ar}) from the climate dataset for Viçosa, Brazil, focusing on the diurnal period with significant solar availability (07:00 to 16:00) (Table 2).

Table 2. Shape Fixity Ratio and Recovery of all analysis coupons.

				Tracker Angle per Time and Temperature ($\alpha_{tracker}$)								
				PLA/TPU								
Hr	T_{ar}	SI	T_{hinge}	10/90	20/80	30/70	40/60	50/50	60/40	70/30	80/20	90/10
	(C°)	(Wh/m^2)	(C°)	(°)	(°)	(°)	(°)	(°)	(°)	(°)	(°)	(°)
7	21.2	310	47	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	21.4	500	63	62.4	57.3	60.9	65.7	65.7	60.0	57.6	56.1	54.4
9	21.2	558	68	71.4	66.8	70.3	74.1	74.1	68.8	65.7	64.1	61.7
10	22.1	706	82	84.0	82.3	85.0	82.7	82.7	80.3	73.0	70.3	63.7
11	25.7	894	101	84.0	82.3	85.0	82.7	82.7	80.3	73.0	70.3	63.7
12	25.5	828	95	84.0	82.3	85.0	82.7	82.7	80.3	73.0	70.3	63.7
13	25.8	848	97	84.0	82.3	85.0	82.7	82.7	80.3	73.0	70.3	63.7
14	26.7	789	93	84.0	82.3	85.0	82.7	82.7	80.3	73.0	70.3	63.7
15	26.5	543	72	78.6	74.4	77.7	80.8	80.8	75.9	72.3	70.3	63.7
16	26.2	420	61	58.8	53.6	57.2	62.3	62.3	56.4	54.3	52.9	51.5

The solar geometry dataset established the theoretical baseline, representing the optimal perpendicular vector to the solar rays required for maximum energy harvesting. Concurrently, the model predicted the surface temperature of the hinges (T_{hinge}), assuming direct thermal conversion of incident solar irradiance.

At 7:00, the solar irradiance (SI) of 310 W/m^2 raised the hinge surface temperature to 47 °C. This value remained below the glass-transition temperature (T_g) of the PLA matrix, thereby maintaining the tracker angle at 0° across all tested specimens. As the diurnal cycle progressed to 09:00, for example, the SI increased to 558.9 W/m^2, pushing T_{hinge} to 68 °C and triggering the release of stored entropic energy within the polymer network. At this hour, the analytical model indicated that distinct material blends yielded varying angular positions: the 90/10 PLA/TPU composite reached a tracker angle of 71.4°, while the 10/90 PLA/TPU blend achieved higher recovery, positioning the panel at 61.7°. Continuous heat absorption ensured that the composite hinges exceeded their T_g, enabling tracking of the solar trajectory until mid-afternoon.

Table 3. Tracking error and potential energy for a sun-tracking system using all SMP blends.

		Tracking Error – $E_{tracker}$ (°)									Potential Energy Generation - η_{energy} (%)									
		PLA ratio (%)									PLA ratio (%)									F.
Hr	α_s	10	20	30	40	50	60	70	80	90	10	20	30	40	50	60	70	80	90	
7	15	14	14	14	14	14	14	14	14	14	97	97	97	97	97	97	97	97	97	73
8	28	34	29	33	38	38	32	30	28	26	83	87	84	79	79	85	87	88	90	
9	41	30	25	29	33	33	27	24	23	20	87	90	88	84	84	89	91	92	94	
10	54	30	28	31	29	29	26	19	16	10	87	88	86	88	88	90	95	96	99	
11	64	20	18	21	18	18	16	9	6	1	94	95	94	95	95	96	99	99	100	
12	68	15	14	16	14	14	12	4	2	5	97	97	96	97	97	98	100	100	100	
13	64	20	18	21	19	19	16	9	6	0	94	95	93	95	95	96	99	99	100	
14	53	31	29	32	30	30	27	20	17	11	86	87	85	87	87	89	94	95	98	
15	40	39	34	38	41	41	36	32	30	24	78	83	79	76	76	81	85	86	92	
16	27	32	27	30	35	35	29	27	26	24	85	89	86	82	82	87	89	90	91	

At noon, the 20/80 PLA/TPU minimized the tracking error to an optimal 2°, closely matching the solar altitude of 68.8°. The 90% TPU blend also demonstrated high accuracy, maintaining an error of 5°. In contrast, the stiffer blends with higher PLA concentrations failed to recover their initial geometry rapidly enough to coincide with the solar zenith, resulting in tracking errors of up to 15° for the 90% PLA specimen.

The results confirmed the substantial advantages of the passive tracking framework by applying the cosine law of illumination to the observed geometric discrepancies. These dynamic applications ensure that the panel surface captures the maximum possible direct solar radiation (SI) by minimizing the angle of incidence between the solar rays and the panel normal. The academic literature corroborates these efficiency gains, with prior research indicating that passive solar trackers achieve 24.86% higher energy-collection

efficiency than fixed systems [7]. The implementation of the 20/80 PLA/TPU hinge theoretically approaches these performance benchmarks, significantly outperforming static reference panels (F. in Table 3) oriented toward the north and adjusted only for the equinoxes. This performance underscores the viability of using thermoplastic blends as functional components in autonomous systems.

Blends dominated by PLA demonstrated superior shape fixity (Table 1), ensuring that the PV module remained securely locked in the eastern-facing morning position. However, these compositions exhibited slower shape-recovery kinetics, resulting in significant tracking errors during peak-irradiance hours (Table 3). Conversely, TPU-rich blends exhibited rapid thermal responsiveness and achieved solar alignment with errors as low as 2° at midday, though their low shape fixity compromised the system's initial structural stability (Table 1). Thus, the analytical model indicates that the 80/20 PLA/TPU composite provides the most effective balance for PV integration. This formulation maintains sufficient structural rigidity to withstand environmental loads during the morning phase while providing the thermal sensitivity required for accurate actuation as solar irradiance peaks. Based on these findings, the authors proposed a passive sun-tracking system utilizing the 80/20 PLA/TPU blend (Fig. 2 a–d).

The proposed tracker operates on a thermal actuation cycle in which the hinge is initially set to a flexed state, facing East (θ_f). As incident solar radiation increases the hinge's internal temperature above the glass transition temperature, the polymer network releases stored entropic energy, driving the hinge toward its permanent flat shape facing West (θ_r).



Fig. 2. (a-b) SMP bent in a 90° angle for facing east; (c-d) tracker facing west with recovered flat shape.

During the late afternoon, the decrease in solar irradiance initiates a cooling phase. In this thermodynamic window, the recovery stress dissipates while the material remains temporarily in a rubbery state before full vitrification. To enable an autonomous night reset without complex actuators or electronic controls, the system could use a continuous-gravity-bias mechanism that inserts an eccentric mass attached to the back of the PV module frame, which exerts a constant downward gravitational bending moment on the hinge. The diurnal cycle relies on the competition between this gravitational load and the temperature-dependent recovery of the PLA. As the recovery force diminishes during cooling, the bias weight overcomes the mechanical resistance of the softened hinge, pulling it back to the initial eastern orientation. Subsequent nocturnal cooling ensures PLA fully vitrifies, rigidly locking the hinge in the deformed state until the following sunrise. To further optimize potential energy generation, the authors suggest integrating

a tilting motor to adjust the PV panel in response to seasonal variations at the solstices and equinoxes, with minimal energy expenditure. Another option would be to manually adjust the system these four times a year.

4 Conclusions

This research validated the use of Shape Memory Polymer (SMP) composites comprising PLA and TPU to develop a passive single-axis solar-tracking structure. The experimental characterization established a direct correlation between the material formulation and the thermomechanical kinematics required for achieving motion. Empirical evaluations demonstrate that the optimal composite for the kinetic hinge (PLA/TPU 80/20) achieved a shape fixity ratio of 91.5% and a recovery ratio of 91.9%, leaving a minimal residual angle of 6.7° upon thermal activation.

The heat transfer analyses confirmed that solar irradiance can raise the surface temperature of the dark-colored SMP hinges above their glass-transition threshold, driving the continuous kinematic alignment of the solar module from the eastern morning position to the western afternoon orientation without electromechanical actuators. By synchronizing the shape recovery profile with the solar trajectory, the proposed tracker could minimize the geometric tracking error to 2° during peak irradiance hours at solar noon. Finally, applying the cosine law of illumination to these geometric discrepancies revealed that dynamic structural positioning would yield an absolute energy-efficiency gain of 22.9% over a north-facing static installation.

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Recycled Fines in Geopolymer Mortar: A Comprehensive Assessment of Mechanical Behavior

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Abstract. The need for sustainable construction materials has driven researchers to find environmentally sustainable substitutes for Portland cement-based construction materials. This paper investigates the mechanical properties of geopolymer mortar produced using very fine recycled aggregates derived from construction and demolition waste. The geopolymer binder used in this study was synthesized from a precursor consisting of a low-calcium aluminosilicate material activated by an alkaline solution. The fine recycled aggregates partially replaced the sand at different percentages varying from 0 to 30%, wherein the impact of washed and unwashed recycled aggregates was evaluated. It was observed from the results of the study that, while the washing of the recycled fines impacted the mechanical behavior the most, all samples made with different substitution rates of recycled aggregates gave comparable mechanical properties. It is expected that integrating recycled fines in geopolymer binders in construction materials will help reduce carbon emissions, decrease construction waste sent to landfills, and promote the construction industry toward sustainable practices.

Keywords: Geopolymers · Recycled aggregates · Mechanical properties · Sustainable construction

1 Introduction

One of the biggest causes of the world's carbon dioxide emissions, energy use, and depletion of natural resources is the construction sector. Ordinary Portland cement (OPC) is a major component of building materials, but its production uses a lot of energy and harms the environment. Because of the high temperatures needed to produce clinker

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and the calcination of limestone, OPC manufacturing is thought to be responsible for 7–8% of the world's CO2 emissions [1]. In response to growing environmental concerns and more stringent sustainability goals, the elaboration of substitutes with lower carbon emissions has emerged as a key component in the building/materials industry. Alkali-activated materials, and among them geopolymers, have become a promising sustainable substitute for OPC. These materials are created by alkaline activation of precursors rich in aluminosilicate, which results in the creation of a three-dimensional network of polymers. According to numerous studies, in comparison to traditional cementitious materials, geopolymer binders can achieve greater mechanical strength, improved thermal stability, and superior chemical resistance [2–4].

Geopolymers exhibit good mechanical properties and environmental advantages, such as decreased embodied energy and greenhouse gas emissions, especially when industrial by-products like fly ash, slag, or calcined clays are used as precursors. The capacity of geopolymer systems to integrate a variety of waste-derived materials, hence promoting circular economy concepts, is an additional benefit. Since construction and demolition waste (CDW) is one of the biggest waste streams produced globally [1]. Although initiatives to recycle coarse aggregates from CDW are growing, fine recycled aggregates are still mostly underutilized. Because of their high water absorption, angular particle shape, and composition variability, these fine fractions are frequently landfilled, which can have a detrimental impact on workability, mechanical performance, and durability when utilized in traditional OPC-based systems [5, 6]. In cement-based mortars, where weak interfacial transition zones and greater water consumption may result in decreased strength and durability, the problems with fine recycled aggregates are more noticeable.

The use of fine recycled aggregates in structural applications is therefore restricted or discouraged by a number of standards and guidelines. Nevertheless, new research indicates that geopolymer matrices might be more resilient to recycled aggregates than conventional cementitious binders. Differences in reaction processes, pore structure refinement, and microstructural evolution in alkali-activated systems are responsible for this enhanced compatibility [7–9]. Although they are frequently seen as harmful in OPC systems, the presence of small particles and residual dust may actually promote matrix densification and geopolymerization reactions.

Despite these promising findings, several aspects related to the use of recycled fine aggregates in geopolymer mortars remain insufficiently explored. In particular, the effect of recycled aggregate processing methods, such as washing, has received limited attention. Washing is commonly applied to remove adhered dust and impurities and to reduce water absorption; however, it may also eliminate fine reactive particles that could otherwise participate in geopolymerization. Furthermore, while mechanical performance has been the primary focus of most studies, the thermal behavior of geopolymer mortars incorporating recycled fine aggregates has not been adequately addressed, despite its importance for energy-efficient and fire-resistant construction applications. This study examines the impact on the compressive strength of geopolymers mortar using washed and unwashed recycled fine aggregates used as partial substitutes for normalized sand.

2 Material and Methods

2.1 Geopolymer Binder

The geopolymer elaborated in this study was synthesized from a low-calcium aluminosilicate precursor, which is metakaolin from industrial grade. Low-calcium precursors are particularly suitable for geopolymerization, as they favor the formation of a stable aluminosilicate gel network with good long-term performance [2, 10].

An alkaline activating solution composed of sodium hydroxide and a sodium silicate solution was produced in the laboratory to initiate geopolymerization. The activator composition and liquid-to-solid ratio were kept constant for all mixtures by following an SiO_2/Na_2O of 1.8.

2.2 Fine Aggregates

Recycled concrete aggregates were obtained from a 6-month-old column, which was crushed using a Los Angeles machine and sieved to achieve a grading comparable to that of natural sand to reach the finest possible at the University of Balamand. The physical properties were determined and are listed as follows: dry specific density (GS)2.21, saturated surface dry specific density 2.36, water absorption 6.98%, and the water content 0.043%. Two types of recycled fine aggregates were investigated: the washed recycled fine aggregates, subjected to water washing to remove dust and loosely adhered particles, and placed in the oven later on to remove the water, and the second batch was prepared using unwashed recycled fine aggregates without any further treatment.

The recycled fines exhibited higher angularity and water absorption than natural sand, consistent with previous findings reported in the literature [6, 11]. Metakaolin, normalized sand, washed recycled aggregates, and unwashed recycled aggregates are the four materials whose particle size distributions are displayed in Fig. 1. The graph shows that most of the metakaolin goes through sieves with sizes smaller than 10 μm, indicating that the particles are extremely fine. The recycled aggregate sizes are comparable to those of normalized sand. The distributions of washed and unwashed recycled aggregates are similar, but the washed aggregates often have slightly smaller particles that pass through the sieves than the unwashed ones, suggesting a more refined particle size following washing. This implies that cleaning the recycled aggregates could enhance their grading and bring their performance closer to that of normalized sand.

2.3 Mix Design

Geopolymer mortar mixtures were prepared by replacing normalized sand with recycled fine aggregates at 10%, 20%, and 30% by mass substitution. Both washed and unwashed recycled fines were evaluated, resulting in six different mixtures. All other parameters were kept constant. Mortar specimens were cast into standard molds (cubic samples of size 4*4*4 cm), compacted, and cured at ambient temperature, as seen in Fig. 2. Compressive strength tests were conducted at 7 and 28 days in accordance with the ASTM standard (C150) [12].

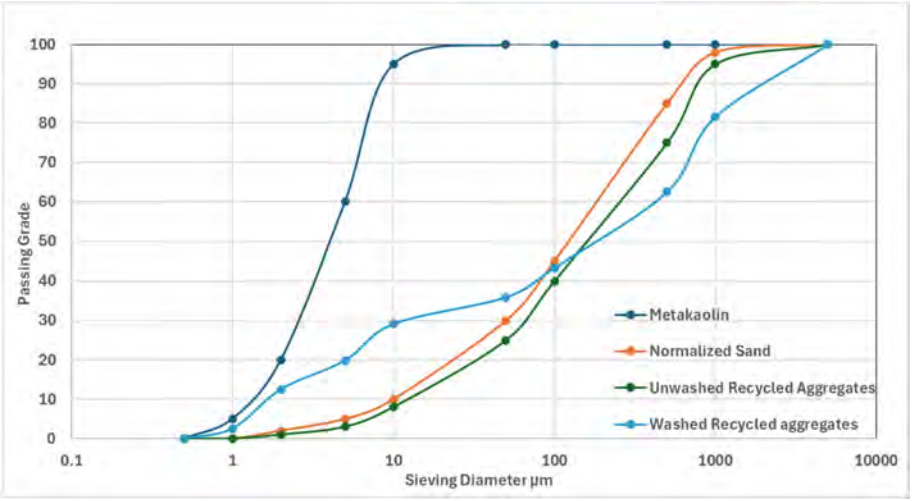


Fig. 1. Sieve analysis of the different materials used.

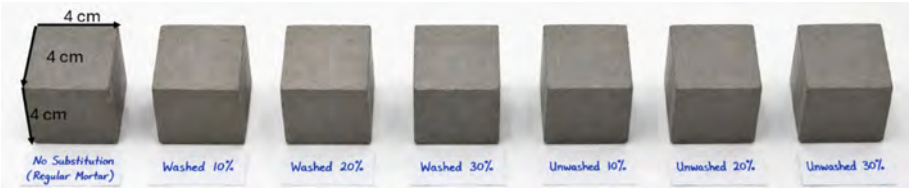


Fig. 2. Elaborated mortars.

3 Results

3.1 Compressive Strength

Figure 3 presents the compressive strength results of geopolymer mortars incorporating washed and unwashed recycled fine aggregates. When assessing the results without taking into account the samples elaborated with 0% of substitution, it is observed that mortars incorporating unwashed recycled fines exhibited significantly higher compressive strength at both curing ages compared to washed mixtures. Nevertheless, it was seen that both types of mixes (washed and unwashed fine aggregates) have similar trends in increasing compressive strength as the geopolymerization reaction occurs. Figure 3 highlights that the unwashed fine aggregates gave the best compressive strength results, even though the washed had remarkably increasing f'c from day 7 to 28. This is explained by the fact that washing eliminated finer particles that could have adhered and developed the matrix that can affect the overall strength of the elaborated material. Samples made from recycled sand generally exhibited mechanical properties demonstrating adhesion within the geopolymer matrix. Nevertheless, the various groups of geopolymers developed promising results at all high substitution rates, even though they didn't reach the values attained with no substitution. Considering the case of the control mortar (0% GFR), it

exhibited the highest strength (38.1 MPa), thus indicating an efficient geopolymerization of the metakaolin binder. The insertion of GFR resulted in a decrease in strength; the 10% and 20% substitution rates decreased to 12 MPa and 10.6 MPa, respectively, likely due to dilution of the reactive binder and weak adhesion at the interface, but primarily due to the lack of silica in the sand used. However, the sample containing 30% GFR showed a slight increase (13.2 MPa at 7 days), suggesting that a higher GFR content could improve particle compaction or provide meso-reinforcement of the solid skeleton within the matrix. At 28 days and with 30% substitution, satisfactory mechanical properties are obtained compared to those obtained with 0% substitution.

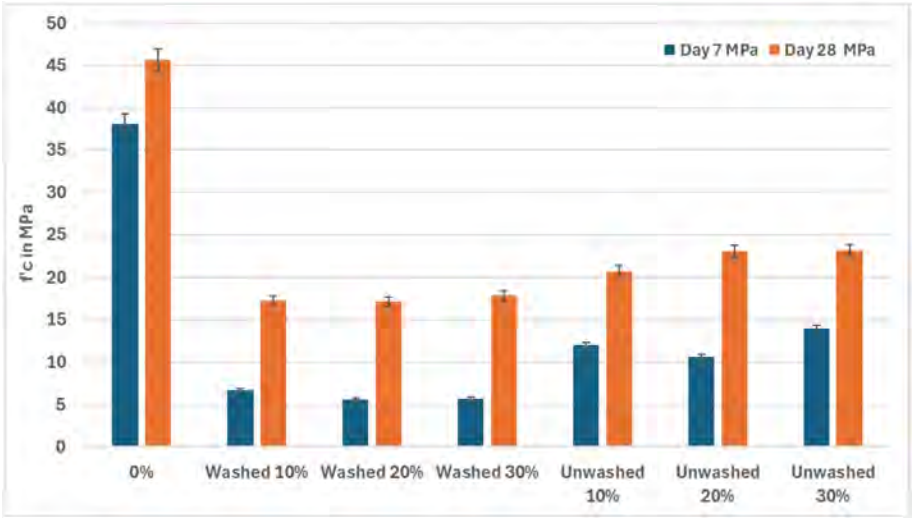


Fig. 3. Compressive strength of geopolymer mortars

As such, it was seen that for washed recycled fine aggregates, increasing the replacement level from 10% to 30% had a limited influence on compressive strength. Conversely, unwashed recycled fine aggregates showed improved mechanical performance with increasing replacement level, particularly at 28 days. This implies that the ability of the geopolymer matrix to acquire greater strength may be hampered by the contaminants in unwashed pebbles. At equivalent replacement levels, unwashed recycled fine mixtures exhibited compressive strengths approximately 80–120% higher at 7 days and 15–35% higher at 28 days compared to washed mixtures. This behavior is attributed to improved particle packing and the presence of residual fines that may participate in geopolymerization reactions [8, 13].

Overall, unwashed recycled fine aggregates are more successful in increasing compressive strength, indicating their superior fit for the creation of high-performance geopolymer mortars, even if the mechanical properties were not as high as those of 0 %. This implies that the presence of unwashed recycled fines could be contributing positively to the geopolymer mortar, possibly by retaining more of the essential minerals or characteristics needed for optimal strength. Moreover, it was seen that the compressive

strength increased/ continued with curing over the 28 days; nevertheless, the percentages of recycled fines with either washed or unwashed characteristics had lower compressive strength compared to the control sample. This distinctive behavior is explained by the incorporation of the recycled aggregate in the mortars, which may possibly affect the bonding strength or hydration properties.

4 Conclusions

The study highlights the impact of recycled fine aggregates on the characteristics of geopolymer mortar, especially with regard to compressive strength. The findings show that using unwashed recycled fine aggregates improves compressive strength more than using washed aggregates, suggesting that it eliminates finer sands that could increase the skeleton development. Overall, recycled aggregates, derived from construction waste, help reduce environmental impact but can decrease the mechanical strength of mortars due to the variability of their properties. The compressive strength of geopolymer mortars, tested at 7 and 28 days, is influenced by the proportion of recycled aggregates used; higher substitution rates (e.g., 10%, 20%, or 30%) lead to a reduction in strength at 10%, followed by a progressive increase at higher rates. This reduction in strength is attributed to a potentially lower bonding capacity and the variability in the quality of the recycled aggregates. However, performance can vary depending on the type and quality of aggregates, and optimizing the mix can improve strength retention. Thus, while the use of recycled aggregates promotes sustainability, it can present challenges in maintaining the desired mechanical performance of geopolymer mortars. Through rigorous optimization of the mix composition and the choice of geopolymer binder, the impact on strength can be mitigated by increasing the substitution rate, making recycled aggregates a viable option for sustainable construction without substantial performance loss. This trade-off between sustainability and mechanical performance underscores the importance of finding the right balance for practical applications in the construction sector.

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Quintuple Helix Approach to Circular Economy: 3D Printed Geopolymer Solutions for Sustainable Built Environments

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Abstract. 3D-printed geopolymers represent a promising low-carbon alternative to conventional cement, offering significant reductions in embodied carbon through the use of waste-derived precursors such as fly ash and slag. Advances in extrusion-based additive manufacturing further enhance sustainability by improving material efficiency, reducing waste, and enabling precise, design-driven resource use. This article applies the Quintuple Helix Model to examine how academia, industry, government, communities, and environmental factors collectively shape the development and adoption of geopolymer 3D printing within circular-economy frameworks. The analysis identifies major opportunities, including policy incentives, digital fabrication capabilities, and cross-sector innovation ecosystems, as well as persistent barriers such as missing standards, scale-up challenges, fragmented governance, and social acceptance gaps. The study highlights the importance of coordinated action, transparent environmental communication, and community-oriented pilot initiatives. It concludes by outlining systemic recommendations to support the mainstreaming of 3D-printed geopolymers as resilient, low-carbon building solutions aligned with circular-economy and climate-neutrality goals.

Keywords: Quintuple Helix Approach · Circular Economy · 3D Printing · Geopolymer · Sustainable Built Environment

1 Introduction

The climate crisis intensifies the need to reduce emissions from the construction sector, one of the largest contributors to global CO_2 output. Cement production alone accounts for 6–8% of global emissions, highlighting the urgency of developing low-carbon binders [1, 2]. In this context, 3D-printed geopolymers have emerged as a promising alternative: they use industrial by-products such as fly ash or slag, significantly lowering embodied carbon while enabling material efficiency through additive manufacturing [3, 4]. As a result, 3D-printed geopolymers represent a compelling alternative to traditional cement systems in the transition toward climate-resilient built environments [5].

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Advances in extrusion-based 3D printing have improved mix design control, rheology and buildability, making geopolymer printing increasingly viable at the construction scale. Simultaneously, the use of waste-derived precursors aligns the technology with circular-economy principles by reducing resource extraction and supporting waste valorisation. By combining low-carbon chemistry with digital fabrication, 3D-printed geopolymers offer a pathway to more sustainable, resilient and adaptive built environments [6, 7].

The main objective of the article is to critically analyse 3D-printed geopolymer technology and its application potential in resilient urban infrastructure, modular housing and disaster-recovery structures. The study adopts the Quintuple Helix Model as its primary analytical framework, enabling a systemic assessment of how 3D-printed geopolymer solutions can support circular-economy transitions by examining interactions among five key subsystems: academia, industry, government, civil society and the natural environment. Unlike existing reviews that predominantly focus on material performance, process optimisation or life-cycle assessment, this paper contributes a systemic innovation-governance perspective by explicitly operationalising the Quintuple Helix model for geopolymer additive manufacturing. This allows identification not only of technological challenges, but also of institutional, social and environmental leverage points shaping real-world implementation

2 Quintuple Helix Model as an Analytical Framework

The Quintuple Helix Model builds on a progressive evolution of innovation frameworks from the Triple to the Quadruple and finally the Quintuple Helix [8, 9]. The Triple Helix model originally conceptualised innovation as the result of interactions between university, industry and government, emphasising their hybrid roles and overlapping functions in knowledge production and economic development. Subsequently, the Quadruple Helix framework added a fourth helix – community (civil society) – to address the criticism that innovation systems often neglect societal needs, values and user perspectives. This extension recognises that citizens, cultural dynamics and communication processes shape both the direction and acceptance of new technologies [10]. The Quintuple Helix further incorporates the environment as a fifth helix, explicitly linking knowledge and innovation to ecological systems and sustainable development. In this model, the five subsystems interact in a co-evolutionary way, making the framework particularly suitable for analysing eco-innovation [11].

It is worth to noticing that this method was not used previously in the context of additive manufacturing, not for geopolymer materials. Its application in the broader field of materials science has also been limited. It is worth citing the work of authors who have explored the Quintuple Helix as a framework for eco-innovation and circular economy transitions in energy and resource systems [12, 13], as well as studies linking the model to sustainable and smart innovation based on recycling process, natural products and bio-based materials [14, 15], which together provide a conceptual foundation for extending the Quintuple Helix approach to sustainable materials engineering and 3D-printed geopolymer solutions. In contrast to techno-centric or policy-only frameworks,

the Quintuple Helix explicitly captures feedback loops between environmental performance, societal acceptance and innovation governance, which are critical for scaling 3D-printed geopolymer technologies beyond experimental pilots.

3 Methodology

Methodologically, the paper follows a Scopus-based systematic literature review combined with helix-oriented qualitative content analysis. First, a structured search strategy was developed, defining the time frame (last 5 years), document types (research articles, reviews, conference papers), and topic relevance to 3D-printed geopolymers and helix-based models. Second, the records retrieved are screened at title, abstract, and full-text levels, and the final corpus is coded according to the five helix dimensions and cross-helix interactions. For each helix, a dedicated coding scheme was used: (1) Academia – research topics (materials design, rheology, structural and durability performance), knowledge transfer, and education for digital fabrication and circular construction. (2) Government – policies, regulatory frameworks, standards, public funding instruments, and green public procurement addressing low-carbon and circular building materials.(3) Industry – business models, technology readiness, demonstration projects, entrepreneurship, and innovation support mechanisms for geopolymer-based 3D-printed solutions. (4) Community – civil society, user perspectives, social acceptance, media narratives, and participatory initiatives in the built environment. (5) Environment – life cycle assessment (LCA), environmental indicators, waste valorization, and uncertainties in ecological performance.

The analysis is guided by the following research questions, which can be grouped along the helix dimensions and their interactions: (1) Cross-helix collaboration: (a) What are the main barriers and opportunities for collaboration among academia, industry, government and communities in implementing 3D-printed geopolymer solutions? (b) Which elements of the Quintuple Helix model enable effective knowledge and technology integration? (2) Government/policy framework: How do regulations and policy instruments influence the development, standardisation and commercialisation of 3D-printed geopolymers within a circular-economy context? (3) Industry, and innovation support: Which entrepreneurship and innovation mechanisms most effectively advance sustainable geopolymer materials and 3D-printed applications? (4) Community and media: How do communities and media shape acceptance, trust and public perception of 3D-printed geopolymer construction? (5) Heuristic identification of synergies and conflicts: How can a helix-based heuristic approach identify synergies and conflicts during the design, policymaking and implementation of geopolymer 3D-printing technologies?

Using these questions, the qualitative synthesis focuses on: (a) mapping barriers and opportunities within and between helices, (b) understanding policy and regulatory drivers or obstacles for commercialization, (c) identifying effective industrial mechanisms and innovation pathways, (d) assessing the role of communities and media in social acceptance, and (e) uncovering synergies and conflicts that affect the scaling of waste-based, low-carbon 3D-printed geopolymer solutions in circular built environments. The final outcome is a set of helix-specific and cross-helix recommendations and a conceptual roadmap for aligning stakeholders to accelerate the deployment of 3D-printed geopolymer technologies. The qualitative synthesis does not aim at statistical

generalisation but at analytical transparency, mapping dominant themes, leverage points and implementation barriers emerging from recent literature.

4 Helix Dimensions Analysis

4.1 Academia Helix: Knowledge, Research and Education

Despite significant progress in rheology optimisation and printability, current academic research focuses predominantly on laboratory-scale performance, with limited emphasis on translation into standardized testing and large-scale implementation [16]. Universities address these gaps by developing skills in digital fabrication and sustainability through FabLabs and project-based learning that integrate prototyping, material testing and circular-economy principles. These interdisciplinary infrastructures create opportunities for training future practitioners, accelerating innovation and supporting collaborative exploration of low-carbon technologies such as 3D-printed geopolymers [4, 17].

4.2 Government Helix: Policies, Regulation and Public Support

Climate and circular-economy policies increasingly steer the shift toward low-carbon construction by promoting resource efficiency, waste reduction and material recirculation. From an industrial perspective, the key challenge is not theoretical feasibility but the alignment of digital fabrication capabilities with reliable business models and predictable regulatory conditions [3, 18]. Regulatory barriers persist, particularly the absence of harmonized codes and standards for 3D-printed and geopolymer-based structures, which hinders their broader adoption despite the clear environmental potential of low-carbon materials. Policy instruments such as green public procurement, tax incentives, and demonstration programs offer promising avenues to accelerate market uptake by aligning financial and regulatory environments with carbon-neutrality goals. In parallel, emerging governance models—such as city-level circularity assessments and national strategies integrating carbon targets—underscore the need for cross-helix coordination among public authorities, industry, academia, and civil society to enable systemic transformation [16].

4.3 Industry Helix: Innovation, Entrepreneurship and Market Uptake

The industrial adoption of 3D-printed geopolymers remains at an early stage, with progress largely limited to pilot-scale demonstrations and specialized niche applications, reflecting ongoing challenges related to rapid setting, limited workability, and interlayer bonding that constrain broader commercialization [3]. Emerging business models in modular housing, resilient micro-infrastructure and disaster recovery increasingly draw on the material efficiency, design flexibility and lower carbon footprint of geopolymer-based additive manufacturing, supported by digital design tools, parametric modelling and BIM-driven optimisation. In the wider Construction 4.0 context, integrated fabrication workflows and platform ecosystems can accelerate adoption through predictive optimisation, robotic extrusion and AI-assisted quality control. However, significant barriers

remain, including scale-up risks, investment uncertainty tied to still-maturing printing technologies, and supply-chain challenges related to the availability and consistency of waste-derived precursors [19, 20].

4.4 Community Helix: Civil Society, Media and Social Acceptance

Public perception of 3D-printed buildings and alternative binders is increasingly shaped by broader narratives around circular construction and sustainable innovation, with media emphasizing the potential of additive manufacturing to reduce waste, improve resource efficiency, and support Europe's transition toward circularity under frameworks such as the EU Circular Economy Action Plan. Stakeholder studies further show that acceptance of circular practices depends heavily on users' and communities' understanding of environmental benefits and their willingness to engage in novel construction approaches [21]. Co-creation environments such as living labs and participatory pilot districts help build public understanding by allowing citizens to engage with new materials, digital fabrication methods and reuse-oriented design strategies, fostering social innovation in the built environment. When combined with inclusive design, these approaches also advance social equity, improving affordability and accessibility in housing and supporting rapid, community-centred post-disaster reconstruction through lower material costs, adaptable modularity and broader access to construction technologies [21, 22].

4.5 Environmental Helix: Ecological Impact and Life Cycle Perspective

While the environmental benefits of geopolymer binders and additive manufacturing in reducing embodied carbon are well established, the Environmental Helix highlights less explored methodological and governance-related challenges [1, 2]. Current life-cycle assessment (LCA) studies of geopolymer-based 3D printing remain fragmented and methodologically heterogeneous. Existing analyses differ significantly in terms of system boundaries, functional units, assumptions regarding precursor availability, energy mixes, curing regimes and end-of-life scenarios. As a result, reported environmental performance indicators are often difficult to compare, limiting their usefulness for standardisation, certification and policy decision-making [7]. This methodological fragmentation constrains the integration of environmental evidence into regulatory frameworks, public procurement criteria and communication with non-expert stakeholders. Without harmonised LCA approaches tailored to digitally fabricated, waste-based construction materials, environmental performance remains weakly translated into actionable governance instruments. Within the Quintuple Helix perspective, addressing these gaps is essential to ensuring that environmental knowledge can effectively guide regulation, market uptake and societal trust in 3D-printed geopolymer technologies [16]. From a circular-economy perspective, the environmental performance of 3D-printed geopolymers cannot be assessed solely through embodied carbon indicators. Operational circularity indicators such as reuse potential, adaptability of printed elements, lifecycle extension through repair or remanufacturing, and design for disassembly remain weakly represented in current assessment frameworks. These aspects are particularly relevant for digitally fabricated construction systems, where geometry, modularity and material composition directly influence end-of-life pathways

5 Discussion: Cross-Helix Interactions: Synergies, Conflicts and Leverage Points

Across all helix dimensions, the absence of harmonised standards, limited large-scale validation and fragmented life-cycle assessment methodologies emerge as systemic rather than sector-specific barriers. These challenges cut across academia, industry, government, communities and environmental governance, reinforcing the need for coordinated Quintuple Helix action rather than isolated, helix-specific interventions.

From a systemic perspective, academia generates knowledge that is insufficiently translated into standardised metrics; industry faces scale-up risks amplified by regulatory uncertainty; governments lack robust, comparable environmental evidence to underpin procurement and certification schemes; and communities encounter fragmented or inconsistent sustainability narratives. The Environmental Helix thus acts not only as a source of boundary conditions but also as a coupling mechanism linking scientific credibility, regulatory legitimacy and social acceptance (Fig. 1).

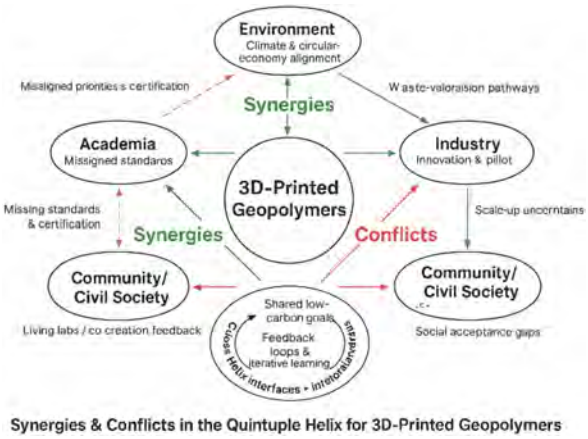


Fig. 1. Quintuple Helix interaction map for 3D-printed geopolymers

The Quintuple Helix framework helps identify key leverage points at these interfaces, particularly performance-based standardisation, harmonised LCA protocols and participatory pilot projects that feed environmental evidence back into governance and market mechanisms. Addressing these leverage points is critical to moving 3D-printed geopolymer solutions from experimental applications toward reliable, circular construction practices. The helix-based analysis reveals three critical leverage points for implementation: (1) performance-based standardisation as a regulatory enabler; (2) pilot-to-procurement transition mechanisms linking demonstration projects with public demand; and (3) narrative and trust-building processes mediated by communities and local governance.

6 Conclusions and Recommendations

The analysis of 3D-printed geopolymers through the Quintuple Helix lens shows that their diffusion in a circular built environment depends less on the material itself and more on integrating knowledge, regulation, markets, society and environmental criteria. Key challenges include missing standards, limited scale-up experience and fragmented stakeholder agendas, though a strong shared driver exists in climate and circular-economy goals and in the potential of digital fabrication.

Recommendations emphasise strengthening cross-helix interfaces. Academia, industry and government should co-develop performance-based standards, LCA guidelines and open testbeds to align regulation with technological maturity. Funding schemes, green-tech incubators and demonstration programmes should require collaboration with communities and transparent communication of environmental performance to build trust. At urban and regional scales, living labs and public procurement can align policy incentives, industrial innovation and community needs, helping shift 3D-printed geopolymers from isolated pilots to mainstream low-carbon, circular construction options. By demonstrating how material innovation, governance structures and social legitimacy co-evolve, the Quintuple Helix provides a robust analytical lens for guiding the transition of 3D-printed geopolymers from experimental technologies to mainstream circular construction solutions.

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From Forest Residue to Structural Material: Mechanical Properties of Invasive Species *Acacia Dealbata* Logs

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Abstract. In response to the increasing demand for timber within sustainability driven construction, this study explores the valorization of forest-management residues generated during invasive species control. The mechanical performance of residual *Acacia dealbata* logs was assessed to evaluate their potential for structural applications. Thirty-four logs (100–150 mm diameter) were harvested in spring 2022 from the primary forest of Peneda-Gerês National Park, northern Portugal, based on visual characteristics such as ovality, straightness, and knotness. After 14 months of air-drying at the University of Minho facilities, 17 minimally processed, natural-debarked logs were selected and visually graded according to the Finnish Voluntary Product Standard for Small Round Timber (VPS-SRT), then industrial oven-dried to approximately 12% MC. Mechanical characterization included non-destructive techniques—longitudinal stress wave and transverse vibration- as well as destructive bending and parallel compression tests following EN 14251:2003. The results were consistent with the VPS-SRT grading, confirming its suitability for field pre-selection. No significant differences were observed between the dynamic modulus of elasticity ($MOE_{lsw} = 18.29$; GPa, SD $= 3.32$ GPa) and the static local modulus of elasticity ($MOE_{m,0} = 17.67$ GPa, SD $= 4.30$ GPa). Bending strength ($f_{m,0} = 111.66$ MPa, SD $= 21.72$ MPa) exceeded reference values for comparable hardwoods, and the characteristic strength corresponded to class D60 under EN 338:2016 for MOE. These findings indicate that *Acacia dealbata* logs possess favourable mechanical properties for structural use, supporting the economic valorization of invasive-species biomass and contributing to environmentally sustainable forest management practices.

Keywords: *Acacia dealbata* · Biomass Valorization · Forest Residues · Invasive Species · Small-diameter Logs

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1 Introduction

Acacia dealbata Link, commonly referred to as Mimosa in Portugal, is an invasive hardwood species native to Australia [1]. Its rapid spread across Mediterranean ecosystems is associated with high adaptability, fast growth, and prolific seed production [2]. Several studies have investigated the valorization of this species through applications such as pulp production, biomass, and other forest byproducts [3, 4]. However, its potential use in the construction sector remains scarce. In the northern Iberian Peninsula, *Acacia dealbata* Link frequently forms dense stands of young trees (10–20 years old), including irregular stems and small-diameter logs. Although these characteristics limit sawn timber yield, previous research suggests that small-diameter logs, when processed minimally, may still exhibit adequate structural performance [5]. Minimal processing may even present advantages, as the outer mature wood remains intact and the structural section surrounding knots is preserved [6, 7].

The mechanical characterisation of logs can be carried out through destructive testing, following standards such as EN 14251:2003 [8] and ASTM D1036–99 [9]. Complementarily, non-destructive testing (NDT) techniques are increasingly employed to support predictive models for evaluating the mechanical performance of standing trees, logs, and sawn timber [10]. These methods allow early material pre-selection without damaging the specimens, which is particularly advantageous when assessing forest residues derived from thinning operations or invasive-species control [11].

Among NDT approaches, acoustic techniques are widely used to estimate wood stiffness. The longitudinal stress wave (LSW) method measures wave propagation velocity, which is related to both stiffness and density. Although logs represent heterogeneous materials, several studies have reported significant correlations between dynamic and static mechanical properties, with coefficients of determination typically ranging from $R^2 = 0.37$ to $R^2 = 0.75$ [10–13]. Another acoustic method is transverse vibration (TV), in which the natural vibration frequency of a log is used to estimate the dynamic modulus of elasticity with $R^2 = 0.85$ to $R^2 = 0.95$ [14, 15].

Despite the growing interest in hardwood resources for structural applications [16], studies addressing the physical and mechanical properties of genus *Acacia* remain limited. In this context, the present study aims to evaluate the mechanical performance of *Acacia dealbata* logs and the predictive capacity of visual grading and selected non-destructive testing (NDT) techniques. This work forms part of a broader research focused on the mechanical characterisation of small-diameter (100–150 mm) *Acacia dealbata* logs with minimal processing, contributing to the valorisation of biomass generated through invasive-species management and control operations.

2 Materials and Methods

Logs of *Acacia dealbata* were harvested in Peneda–Gerês National Park (northern Portugal), where this invasive species poses a significant threat to native biodiversity [17]. A total of 34 logs (2 m in length and 100–150 mm in diameter), exhibiting lower misalignment and reduced number of visible defects, were selected and felled in spring 2022 with the assistance of the Portuguese Institute for Nature Conservation and Forests

(ICNF). Green moisture content (MC) was determined from discs extracted from each log in accordance with ISO 13061-1 (2014), yielding a mean value of 70.9% (SD = 5.78%).

After transport to the laboratories of the University of Minho (Guimarães), the logs were visually characterised in accordance with EN 14251:2003 [8] definitions. The characterisation included measurements of apparent diameter, ovality, taper and sweep. Visual grading was performed according to the Finnish Voluntary Product Standard for Small Round Timber (VPS-SRT) [18]. Except for sweep, seventeen logs (90–143 mm in diameter) satisfied the grading requirements and were classified as Grade A (superior) or Grade B (medium), while the remaining seventeen logs were rejected. The selected logs were stored indoors and allowed to air-dry under protected conditions.

Subsequently, kiln drying was carried out using an industrial drying schedule designed for *Eucalyptus* species until an average moisture content (MC) of approximately 12% was reached. Non-destructive testing (NDT) was then performed using the Longitudinal Stress Wave (LSW) and Transverse Vibration (TV) techniques. During testing, MC was measured with a calibrated electrical resistance moisture meter in order to adjust the results to the corresponding moisture conditions.

For the LSW tests, logs were positioned horizontally and excited by a hammer impact while an accelerometer recorded the resulting stress-wave response. Wave velocity (v, mm s^{-1}) and the dynamic modulus of elasticity (MOE_{lsw}, GPa) were calculated from the fundamental resonant frequency (f_{LSW}, Hz), the specimen length (L, mm), and the full-body density (ρ, kg m^{-3}), according to Eqs. (1) and (2):

$$v = 2Lf_{LSW} \tag{1}$$

$$MOE_{lsw} = v^2\rho \tag{2}$$

For the TV tests, logs were suspended at their nodal points under free–free boundary conditions. The natural frequency of the first vibration mode (f_1, Hz) was recorded and used to estimate the dynamic modulus of elasticity (MOE_{tv}) based on Euler–Bernoulli beam theory:

$$MOE_{tv} = \frac{4\pi^2 f_1^2 m L^3}{4.74\, I} \tag{3}$$

where m is the mass (kg), L is the log length (mm), and I is the second moment of area (mm^4), calculated from the mean apparent diameter.

After NDT measurements, destructive four-point bending tests were performed according to EN 14251:2003 [8] to determine the local modulus of elasticity in bending parallel to the grain ($MOE_{m,0}$), adjusted to 12% MC following EN 384:2016 [19]:

$$MOE_{m,0} = \frac{\Delta M}{\Delta w_l}\frac{c^4}{6I_l}\left[-\frac{1}{(c + l_l/2)^2} - \frac{D}{2} + \frac{1}{c^2}\right] \tag{4}$$

$$D = \left(\frac{1}{c^2} - \frac{1}{(c + l_l)^2}\right) \tag{5}$$

$$c = \frac{l_1 d_1}{d_2 - d_1} \tag{6}$$

$$I_l = \frac{\pi r^4}{4} \tag{7}$$

where ΔM is the increment of bending moment within the linear portion of the load–deformation curve (Nmm), and Δw_l is the corresponding increment of displacement (mm). The parameters d_1 and d_2 denote the minimum and maximum apparent diameters within the gauge length (mm), respectively; I_l is the smallest second moment of area within the gauge length (mm^4); and l_l is the local gauge length (mm).

Bending strength ($f_{m,0}$, MPa) was also determined according to EN 14251:2003 using:

$$f_{m,0} = \frac{16 F_{max} a}{\pi d_h d_v^2} \tag{8}$$

where F_{max} is the maximum total load applied by both loading heads (N), a is the distance between the loading position and the support (mm), d_v is the diameter measured in the direction of loading at mid-span (mm), and d_h is the diameter measured perpendicular to the loading direction at mid-span (mm).

Prior to destructive testing, logs were conditioned at 20 °C and 60% relative humidity until constant mass was achieved. After testing, MC and density were determined from samples taken near the failure zone using the oven-dry method (ISO 13061-1) and the immersion method (ASTM D2395), respectively.

Statistical analyses included descriptive statistics, independent-sample *t*-tests, and correlation analyses conducted at a 95% confidence level. All analyses were performed using the Real Statistics add-in for Microsoft Excel® 2021.

3 Results and Discussion

All 34 logs presented curvature values exceeding the limits defined by VPS-SRW grading rules: Sweep over 5.0 mm/m for grade B [18]. Curvature affects log performance in two main ways. First, excessive curvature may reduce timber yield during processing. However, this aspect is less relevant in the present study. Second, pronounced curvature may affect structural behaviour under compression parallel to the grain due to potential second-order instability effects (buckling). However, these limits were developed for coniferous species from managed forests grown specifically for construction purposes. In contrast, the logs analysed in this study originated from unmanaged stands and developed without silvicultural control or a predefined end use. Moreover, Hofmann et al. [22], studying rustic German oak logs with comparable curvature levels, reported no statistically significant correlations between curvature and bending strength. This suggests that the VPS-SRW [18] curvature limits may be conservative when applied to minimally processed hardwood logs.

Regarding visual grading, Fig. 1 groups the logs according to VPS-SRW [18] assignable grades. Of the sample, four logs (23.5%) were classified as grade A and

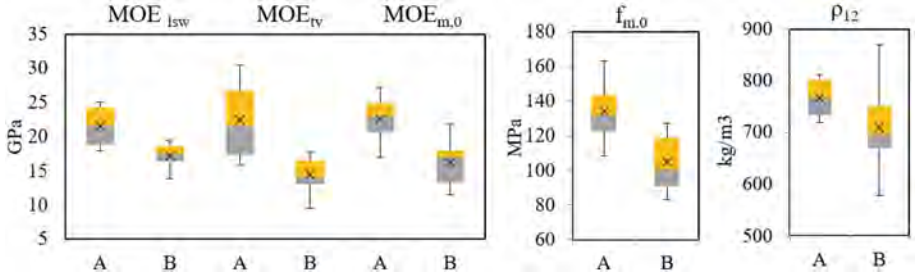


Fig. 1. Comparison based on the VPS-SRW grading system [18] of *Acacia dealbata* logs classified as Grade A (superior) and Grade B (intermediate) for different parameters: MOE_{lsw}, MOE_{tv}, $MOE_{m,0}$, bending strength ($f_{m,0}$), and density (ρ_{12}) adjusted to 12% MC.

thirteen (76.5%) as grade B. Specimens assigned to grade A generally exhibited higher mechanical performance. Nevertheless, Welch's *t*-tests comparing mean values between grades yielded *p*-values above 0.05, indicating no statistically significant differences. The parameters closest to significance were the local modulus of elasticity $MOE_{m,0}$ ($p = 0.055$) and bending strength $f_{m,0}$ ($p = 0.074$).

Table 1. Statistical summary of modulus of elasticity (MOE) values.

Property	Mean	SD	COV	Max	Min	*n*
	GPa	GPa	%	GPa	GPa	
MOE_{lsw}	18.29	3.32	18.12	25.91	12.90	17
MOE_{tv}	16.32	4.97	30.43	30.48	9.52	17
$MOE_{\mathrm{m,0}}$	17.67	4.30	24.33	24.33	11.59	17

Table 1 summarizes the descriptive statistics for all the moduli of elasticity studied. No significant differences were observed between the local MOE and the MOE_{lsw} ($p = 0.48$) and the MOE_{tv} ($p = 0.11$), respectively. However, after removing outliers from the MOE_{tv} dataset (reducing the number of specimens to 15), statistically significant differences were observed between MOE_{tv} and the local modulus of elasticity ($MOE_{m,0}$). These findings suggest the potential for predicting the modulus of elasticity ($MOE_{m,0}$) using longitudinal stress wave measurements. As an example, Eq. (9) presents a simple linear regression model with a coefficient of determination of $R^2 = 0.628$.

$$MOE_{\mathrm{m,0}} = -1.13 + 1.03 MOE_{\mathrm{dyn,lsw}} \tag{9}$$

Figure 2 presents bending strength and density results. The mean bending strength was 111.7 MPa (SD = 21.72 MPa), while the mean density adjusted to 12% MC was 723.0 kg/m^3 (SD = 69.14 kg/m^3). The mean MC during the bending tests was 12.21% (SD = 0.95%). Based on these values and the measured local modulus of elasticity, reference characteristic values were estimated following EN 384:2016 [19]. The results

correspond to a strength class equivalent to D75 for bending strength $f_{m,0}$, D60 for modulus of elasticity (MOE_{local}), and D45 on density (ρ_{12}).

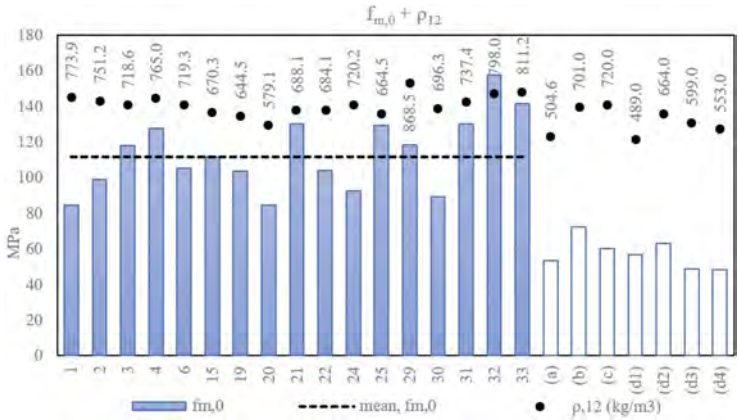


Fig. 2. Filled bars represent the bending strength values ($f_{m,0}$), while the dots indicate the density adjusted to 12% MC for each log. The white bars and their corresponding dots compare these results with the mean values of $f_{m,0}$ and density reported in other studies: (a) *Acacia dealbata* boards from south-central Chile [20]; (b) *Acacia melanoxylon* boards from northern Portugal [21]; (c) oak logs (*Quercus petraea* (Matt.) Liebl.) from Rhineland-Palatinate, Germany [22, 23]; and hardwood logs from Ireland: (d1) alder (*Alnus glutinosa* (L.) Gaertn.), (d2) European ash (*Fraxinus excelsior* L.), (d3) European birch (*Betula pendula* Roth. and *Betula pubescens* Ehrh.), and (d4) sycamore (*Acer pseudoplatanus* L.) [24].

Also, Fig. 2 compares the bending strength values with results reported in previous studies. Although significant differences in bending strength are observed, density values are closer to those reported for *Acacia melanoxylon* boards (701 kg/m^3) and rustic oak logs (720 kg/m^3). Indeed, comparable trends are also reported for global modulus of elasticity in those studies.

4 Conclusion

The results suggest that the scope of visual grading is limited; however, it may still serve as a useful pre-selection tool for logs at the field level. In contrast, the results obtained from dynamic testing—particularly the longitudinal stress wave method—indicate a promising potential as a reliable non-destructive grading technique.

Overall, the outcomes of the destructive tests support the potential structural use of minimally processed *Acacia dealbata* logs, contributing to the valorisation of biomass generated during invasive-species management operations. Nevertheless, further studies with larger sample sizes are required to improve the statistical robustness of the results and to refine grading criteria for this type of material.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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Circular Thinking Through Biomimicry: The Case of the Eden Project

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Abstract. This paper examines biomimicry as a strategic response to contemporary environmental and socio-economic challenges, emphasizing its potential to support sustainable and circular approaches in architectural design and construction. The study addresses environmental pressures across Europe, particularly in the Mediterranean region as a significant example, through statistical insights from Eurostat and climate data analyses from the Copernicus Interactive Climate Atlas. A qualitative case study methodology is applied through the sustainability-oriented evaluation of the Eden Project in Cornwall across the three pillars of sustainability: environment, economy, and society. The Eden Project is selected as a representative example of ecosystem-level biomimicry, demonstrating the application of bio-inspired principles across ecosystem, architectural, and material scales through the transformation of an inactive quarry into a functioning ecosystem, the geodesic structural system inspired by Buckminster Fuller, and the use of ETFE as a lightweight and energy-efficient material solution. The identified biomimetic principles — including adaptation, resource efficiency, and regenerative processes — highlight biomimicry's potential to enhance environmental performance, resilience, and circularity within the built environment across different climatic regions, including the Mediterranean. The study also highlights the growing need for workforce upskilling to support innovative design methodologies. Within this context, the course "Bio-inspired innovation and design for sustainable engineering solutions", developed by the Cyprus University of Technology under the BuildSkills Academy Centre of Vocational Excellence (CoVE), is presented as an initiative supporting bio-inspired design education.

Keywords: Ecosystem-level biomimicry · Circular design · Sustainable architecture · geodesic structural system · ETFE · BuildSkills Academy

1 Introduction

The role of architecture as an expression of the relationship between humans and nature has long been debated across different historical periods and cultures [1]. Today, architecture is undergoing a transformation shaped by climate change, environmental awareness

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and pressure on natural resources. In this context, biomimicry has emerged as a design methodology that explores how strategies found in nature can inform more resilient and adaptive built environments [2].

Current environmental challenges across Europe highlight the need for regenerative and circular design strategies, with the Mediterranean region serving as an example of increasing environmental pressures and climate-responsive design needs. As a representative example of ecosystem-level biomimicry, the Eden Project in Cornwall is examined as a case study demonstrating the application of bio-inspired principles across multiple design scales.

The study adopts a qualitative case study approach combining climate data analysis, theoretical investigation of biomimicry and sustainability-oriented evaluation of the Eden Project across ecosystem, architectural, and material scales through the three pillars of sustainability: environment, economy, and society. The findings highlight the potential of biomimetic and regenerative strategies to enhance circularity, environmental performance, and resilience across different environmental contexts, while emphasizing the growing need for education and professional training in bio-inspired design methodologies, reflected through initiatives developed within the BuildSkills Academy [3].

2 The Current Demand for Sustainable Built Environments

Contemporary challenges such as climate change, energy crises, geopolitical instability, supply chain disruptions, and resource depletion highlight the need for innovative design and construction methodologies. At the same time, the construction sector remains one of the most resource-intensive industries, contributing significantly to material consumption and environmental impact [4]. This section examines environmental data from Eurostat and the Copernicus Interactive Climate Atlas to highlight environmental pressures across Europe, using the Mediterranean region as an example of the growing need for circular, regenerative, and resource-efficient design approaches within the built environment.

2.1 Eurostat: Final Energy Consumption in the Industry Sector and Raw Material Consumption in Europe, 2023

Buildings depend heavily on energy and material resources, contributing substantially to the depletion of natural reserves. Final energy consumption is a key indicator of energy use within the secondary sector. In this context, Central Europe records the highest levels, ranging from 11,638.50 to 50,065.86 thousand tonnes of oil equivalent (see Fig. 1). In addition, Raw Material Consumption (RMC) measures the total amount of natural resources used by an economy. In 2023, the European Union consumed approximately 6.6 billion tonnes of raw materials, a significant share of which consisted of mineral construction materials such as concrete, gravel, sand, and stone [5]. The construction sector, as a highly energy- and material-intensive industry, consumes nearly 50% of extracted raw materials, making it a major contributor to environmental pressures [4].

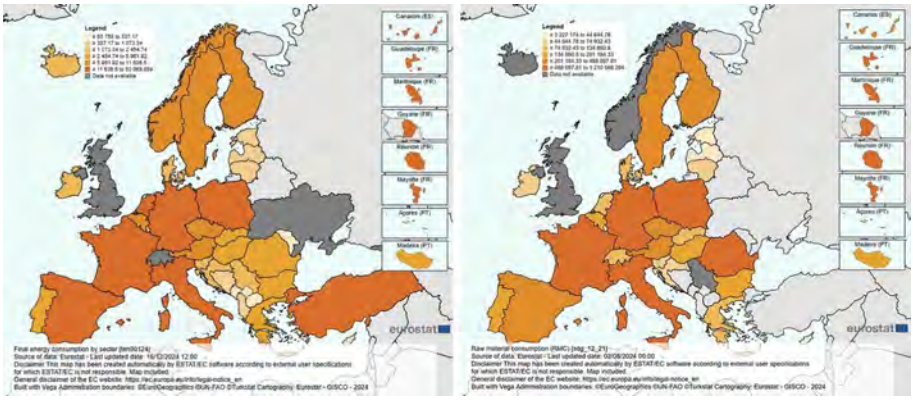


Fig. 1. Final Energy Consumption in the Industry sector (Left) [4] and Raw Material Consumption (Right) in Europe, 2023 [5].

2.2 Climate Data Analyses Through the Copernicus Interactive Climate Atlas: The Mediterranean Region as a Paradigm

The past decade has been recorded as the warmest on record, with global average temperatures projected to approach an increase of 2 °C by 2050 according to the Copernicus Interactive Climate Atlas. However, the Mediterranean region provides a representative example of seasonal temperature changes. Under the Global Warming Level (GWL) 2 °C scenario, winter temperatures are projected to increase by approximately 1.4 °C, while summer temperatures may reach increases of up to 2.5 °C (see Fig. 2) [6]. Transitional seasons such as spring and autumn are projected to warm considerably, progressively losing their distinct climatic characteristics due to increasing overheating trends.

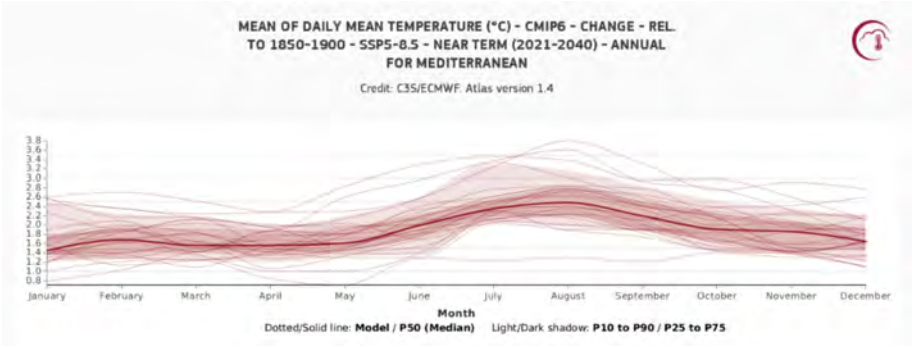


Fig. 2. GWL 2 °C-Mediterranean: Seasonal average of daily mean temperature [6].

3 Human-Nature: Architecture as a Mediator

The extensive use of fossil fuels and natural resources has significantly transformed atmospheric composition and climatic patterns over the past two centuries. At the same time, the relationship between humans and nature has always been characterized by strong interdependence. Architecture therefore acts as a mediator within this relationship, shaping social, economic and ecological dynamics. According to Gruber (2011), incorporating principles derived from natural systems into the design process can contribute to more adaptive and sustainable built environments [7], forming the basis for biomimetic approaches in architecture.

4 Biomimicry as a Design Methodology

The term biomimicry derives from the Greek words bios (life) and mimesis (to imitate), meaning "to imitate life". It refers to the study and emulation of nature's forms, systems, and processes in order to address human challenges and develop sustainable design solutions [2]. In natural systems, organisms use locally available resources and reintegrate materials into ecological cycles powered primarily by solar energy. This reflects the circular character of natural systems, where materials and energy circulate through closed-loop cycles of reuse, transformation, and regeneration rather than waste production [8].

The concept gained wider recognition through Janine Benyus's book Biomimicry: Innovation Inspired by Nature [9], which framed biomimicry as learning from nature's models to develop environmentally responsible technologies. Subsequent research has expanded the application of biomimicry within architecture and engineering, with Gruber examining it as a framework for architectural innovation [7] and Pawlyn emphasizing its potential for resource-efficient engineering solutions [10].

4.1 Framework of Biomimicry

In recent years, alternative "sustainable" or "green" design approaches have emerged with the aim of reducing the environmental impacts of the built environment. Biomimicry extends beyond the imitation of natural forms, involving a systematic process of studying nature's strategies and translating them into circular and sustainable design principles.

Two main approaches can be identified: the Top-Down approach, where a design problem initiates the search for biological analogies, and the Bottom-Up approach, where biological observations inspire technological applications [2]. Biomimicry can also be understood through three levels of imitation: organism, behavior, and ecosystem. These levels define whether inspiration derives from individual biological structures, organism–environment interactions, or broader ecological systems. Among them, ecosystem-level biomimicry is particularly relevant to regenerative and circular design approaches, as it focuses on the relationships, flows, and adaptive processes found in natural ecosystems rather than on isolated biological forms [11].

5 Case Study: The Eden Project as a Multi-Scale Biomimetic Model

The Eden Project is examined as a significant example of ecosystem-level biomimicry and regenerative design, applying bio-inspired principles across urban, architectural, and material scales. Located in Cornwall, United Kingdom, it is a pioneering ecological complex composed of biome domes representing ecosystems from different climatic regions, completed in 2001 by Nicholas Grimshaw & Partners through the regeneration of an abandoned clay quarry into a new habitat (see Fig. 3) [12].

5.1 Biomimicry Across Design Scales

Biomimetic principles are applied across multiple design scales in the Eden Project. At the ecosystem level, the biome structures draw inspiration from hexagonal honeycomb formations and soap-bubble geometries, illustrating efficient structural organization found in natural systems. These geometries enable large enclosed spaces to be constructed with minimal material use while maintaining structural strength and adaptability. At the organism level, the project reinterprets the geodesic principles associated with Buckminster Fuller through a contemporary architectural application. At the material scale, the domes are clad with ETFE cushions composed of three inflated layers that improve thermal insulation while allowing high levels of natural light transmission [13].

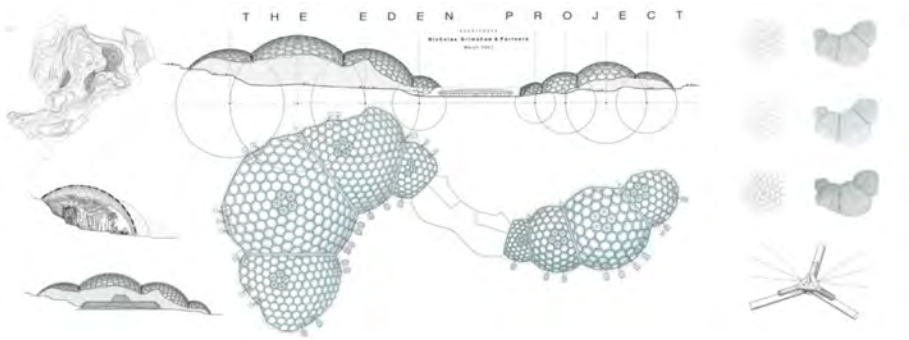


Fig. 3. Architectural Drawings of the Eden Project [12].

5.2 Environmental, Economic and Societal Performance

The Eden Project is qualitatively evaluated through the three pillars of sustainability to assess the environmental, economic, and societal implications of biomimetic design strategies across ecosystem, architectural, and material scales. The transformation of a degraded quarry into a functioning ecological complex reflects a regenerative approach that reconnects built and natural systems, while reinforcing the human–nature relationship through the circular reuse of an inactive quarry landscape.

Biomimetic principles are applied across ecosystem, architectural, and material scales through the quarry regeneration, the geodesic structure, and the ETFE envelope system as a lightweight and energy-efficient material solution. With a weight of approximately 1% of double glazing, ETFE enables a lighter structural framework while maximizing daylight and solar gain, reducing heating demand, material consumption and construction costs [13]. Studies on ETFE systems indicate improved energy efficiency, reduced construction time, and lower embodied environmental impact compared to conventional glazing systems [14]. In addition, the reduced steel use of the hexagonal structure lowers the embodied carbon footprint, while the recyclable and replaceable ETFE cushions improve maintenance efficiency and extended service life. However, despite its lightweight and recyclable properties, the long-term circular performance of ETFE systems still depends on material recovery processes and end-of-life management.

Beyond its environmental performance, the project has contributed to the economic revitalization of Cornwall through tourism, regional development and employment [12]. It also functions as an educational and cultural hub promoting environmental awareness and sustainability. Overall, the project illustrates how biomimetic design strategies can support circular thinking through efficient material use, adaptable structures, and the regenerative reuse of existing landscapes. Table 1 summarizes the sustainability performance of the project across ecosystem, organism, and material scales.

Table 1. Sustainability Assessment of biomimetic design strategies in the Eden Project.

Design Principles	Environment	Economy	Society
1. Ecosystem scale – Quarry regeneration	+ Urban regeneration, landscape reuse and regenerative site transformation + Habitat creation	+ Contribution to the regional economy through tourism	+ Education, tourism, and job creation
2. Organism scale – Geodesic structure	+ Adaptation to unstable quarry terrain + Biomimetic cellular geometries integrated with the landscape	+ Reduced structural weight, steel use and material consumption + Faster and more economical construction	+ Architectural inspiration + Integration with nature
3. Material scale – ETFE envelope system	+ Lower embodied carbon footprint + Natural lighting and ventilation +Recyclable and replaceable material with reduced construction waste	+ Reduced construction and operational costs + Improved energy efficiency + Lower maintenance requirements and extended service life	+ Technological innovation and educational value

6 Biomimicry as a Pathway Toward Sustainability, Circularity and Design Education

Biomimicry is widely recognized as a design methodology based on the fundamental principles of natural systems identified through the framework of Life's Principles [8], including adaptation, local responsiveness, resource efficiency, environmentally compatible processes, and regenerative cycles. These principles reflect how materials and energy circulate through reuse, transformation, and regeneration rather than waste production, as expressed by Richter (2011): "Nothing is lost, nothing is created, everything is transformed" [14]. Projects such as the Eden Project illustrate how landscape regeneration, structural efficiency, and lightweight materials can support regenerative and circular architectural approaches, highlighting biomimicry's potential for climate-responsive and sustainable design across different contexts.

The transition toward sustainable and circular built environments also highlights the growing need for new professional skills in design and engineering, while many vocational education and training (VET) programmes in Europe still do not fully address current environmental and technological challenges [15]. Within this framework, the pilot course "Bio-inspired Innovation and Design for Sustainable Engineering Solutions", developed by the Cyprus University of Technology under the BuildSkills Academy Centre of Vocational Excellence (CoVE), introduces biomimicry through the Copernicus Interactive Climate Atlas (monitoring climate change), AskNature.org (exploring biological models), and Life Cycle Assessment (LCA) for evaluating environmental impacts, while examining case studies such as the Eden Project as a pedagogical example of ecosystem-level biomimicry and circular design strategies [3].

7 Discussion and Conclusion

Contemporary environmental challenges require architecture to operate within ecological limits while responding to human needs. The sustainability-oriented evaluation of the Eden Project identified positive environmental, economic, and societal impacts across ecosystem, architectural, and material design scales, demonstrating how ecosystem-level biomimicry can support circular design strategies. The environmental pressures identified in the Mediterranean region further highlight the relevance of ecosystem-level biomimetic strategies for developing climate-responsive solutions across different climatic contexts. The study also highlights the importance of education and workforce upskilling for the effective adoption of innovative design methodologies.

Although the study supports the potential of biomimetic strategies through literature-based and technical analysis, the absence of direct comparative assessment with conventional construction systems constitutes a limitation of the research and highlights the need for future quantitative evaluation of environmental and energy performance. In addition, biomimicry presents practical limitations in real-world applications, as many existing examples focus on isolated systems rather than integrated architectural approaches. Its implementation often depends on interdisciplinary collaboration, advanced technologies, and increased construction costs, while biological principles cannot always be directly transferred across scales. Despite these limitations, biomimicry remains

a promising framework for supporting regenerative, circular, and climate-responsive approaches within the built environment.

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Local Stone Techniques. New Eco-Friendly Meanings for the Community

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Abstract. In the paper the authors afford the question of stone viewed not only as the most antique construction material, but also as a new sustainable material of contemporary masonry techniques. At the same time, the relationship between the building, the soil, and the place will be explored, considering how the raw materials used for construction come directly from the local context. This continuity creates a strong harmony between architecture and landscape and establishes an identity link between the buildings and the land. Six points of reflection for an environmental design will be lightened: health reliability, local resources, perceptual adaptability to landscape, long-lasting durability, the possibility of reusing recycled material, and bioclimatic performance. In a second part of the paper, the authors will propose a series of contemporary realised case studies and experimentations. Finally, a perspective of the significance for communities of returning to this antique value is prospected.

Keywords: Stone · executive techniques · community · sustainability · landscape · contemporary project

1 Stone Architecture and Landscape: Local Resources and Sustainable Strategies for Contemporary Construction

1.1 Stone, Territory and Identity of the Built Landscape

Building with stone represents a practice as ancient as architecture itself. Since the earliest forms of permanent settlement, humans have identified in this material a resource capable of ensuring stability, protection, and durability over time. Stone has not only been a material readily available in the territory, but also a substance that has helped define the relationship between human beings and the natural environment. Through its processing, a constructive culture developed based on craftsmanship, knowledge of the physical properties of materials, and careful observation of the characteristics of place. Over the centuries, these skills have been transmitted through artisanal practices and local building traditions, contributing to the formation of a technical and cultural heritage deeply rooted in the territories and communities that inhabit them. Stone architecture, understood as the construction of buildings with load-bearing stone masonry, represents a well-established building technique characterized by a long history. In many geographical con-texts,

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stone has long been the primary building material, adapting to climatic conditions, the availability of natural resources, and the construction techniques developed over time. From the monumental architecture of antiquity to rural settlements and historic European centers, stone construction has played a decisive role in shaping inhabited landscapes and defining the identity of places. A particularly significant aspect concerns the relationship between building, ground, and territory. In many building traditions, the raw material used for construction came directly from the surrounding context or even from the very site of construction (Fig. 1).



Fig. 1. Castle of San Michele, Avella, Italy

This continuity between ground and building generates a harmonious relationship between architecture and land-scape. Buildings share colors, textures, and morphological characteristics with the natural environment, contributing to the formation of coherent and recognizable landscapes. Construction does not appear as an external element but rather as a natural transformation of the territory's resources. The local origin of materials also assumes an identity value. Architecture becomes an expression of the available resources and the construction knowledge developed by the com-munities inhabiting a particular place. In this way, buildings appear deeply rooted in the geographical and cultural context, strengthening the sense of belonging between construction and landscape. Stone architectures, widespread in many rural and urban contexts, therefore testify to a direct relationship between humans, available raw materials, and the environment in which human settlements develop. During the twentieth century, the introduction of industrial materials and standardized building systems, such as reinforced concrete, progressively modified this relationship between architecture and territory. Industrialized techniques made it possible to produce buildings more rapidly and in a replicable way, often independent of the characteristics of place. In many urban and peri-urban contexts, this process contributed to the spread of uniform building models in which the connection with local resources and the landscape has gradually weakened. The loss of

this relationship between construction and context has generated increasingly homogeneous urban landscapes, sometimes lacking references to the geographical and cultural specificities of territories.

1.2 Survey Methodology and Analysis of the Case Studies

The research included a phase of direct field investigation aimed at the analysis of several representative case studies of traditional stone architecture located within the territories of the *Ager Nolanus* and Irpinia. Regarding the *Ager Nolanus* area, portions of the masonry of the Medieval Castle of Avella and a traditional rural building were examined, selected for their historical and constructive value as well as for the significant presence of local limestone building techniques. Concerning the Irpinian territory, the case study focused on a rural stone building located in the municipality of Montemarano, representative of the traditional construction techniques widespread in the inland areas of Campania. The selection of the buildings was carried out by considering different rural and historical contexts, with the aim of identifying significant examples in terms of construction characteristics, state of conservation, and relationship with the surrounding landscape. Field observation made it possible to investigate the relationship between traditional building techniques, local resources, and the morphology of the territory.

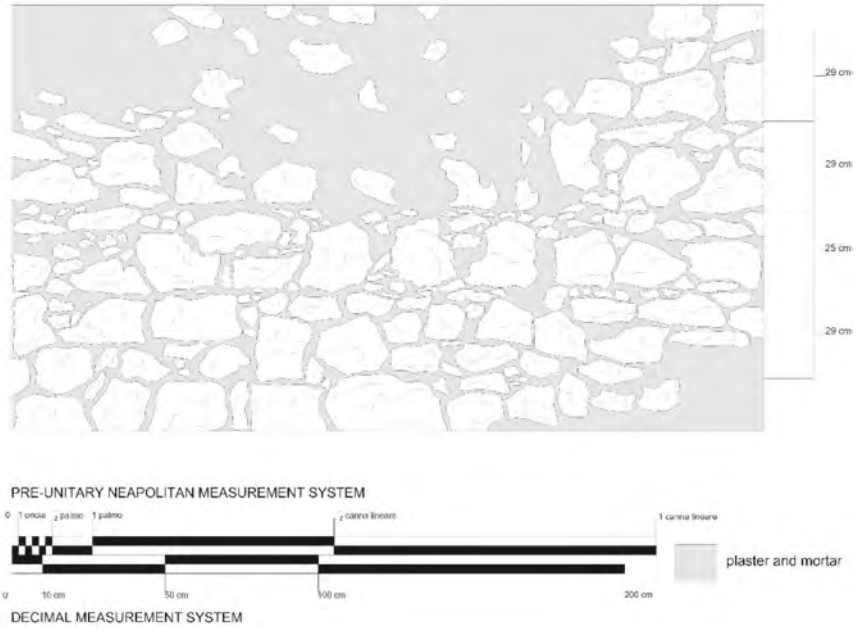


Fig. 2. Wall sample of Avella Castle, with masonry "a cantieri".

The survey methodology adopted was based on an integrated approach including direct survey, photographic documentation, material analysis, and stratigraphic reading of the masonry. Through close observation of the wall surfaces, it was possible to

identify the different techniques used in the laying of stone elements, analyzing the arrangement of the stones, assembly methods, dimensions of the blocks, and the presence of connecting or wedging elements. Particular attention was devoted to the study of masonry textures, considered as expressions of the construction knowledge developed by local communities over time. The analyzed masonry structures (Fig. 2) are mainly composed of local limestone, used in irregular or roughly hewn forms and arranged according to traditional construction techniques closely connected to the availability of stone materials and to the building practices characteristic of the *Ager Nolanus* and Irpinia territories. The analysis of the masonry highlighted how construction techniques were strictly related to the availability of natural resources within the territory and to the artisanal processing of stone materials. In many cases, the geometric irregularities of the stones were compensated through specific laying methods capable of ensuring structural stability and wall continuity. The stratigraphic reading of the buildings also made it possible to identify subsequent transformations, extensions, and maintenance interventions, providing information about the evolutionary phases of the constructions. The different masonry techniques observed testify to continuous adaptation processes linked to the functional, climatic, and productive needs of the settled communities. The investigation also included the analysis of the relationship between the buildings and the environmental context, considering orientation, exposure, wall thickness, and landscape integration. These elements helped to understand how stone architectures were designed according to principles of passive climatic adaptation, exploiting the thermal properties of stone materials to improve indoor comfort and reduce energy demand. The in-depth study of the case studies therefore represented not only an activity of documentation of the existing built heritage, but also a tool for understanding traditional construction logic. The comprehension of building techniques and of the relationships between materials, territory, and architecture constitutes a fundamental basis for future strategies of conservation, restoration, and contemporary reinterpretation of stone constructions.

1.3 Stone as a Sustainable Resource for Contemporary Design

Within this scenario, stone can be reinterpreted not only as the oldest building material, but also as a contemporary resource capable of contributing to the development of design strategies oriented toward environmental sustainability. Its intrinsic properties and its direct relationship with the territory make it possible to consider it as a reference material for design approaches attentive to the relationships between architecture, environment, and natural resources. Reflection on the role of stone in environmentally conscious design can be articulated through several fundamental principles. In particular, six key aspects highlight the potential of this material within contemporary construction processes (Table 1). The first concerns health reliability. Stone is a natural material characterized by a mineral composition free of harmful emissions. Its use therefore contributes to ensuring healthy indoor environments, reducing the presence of potentially harmful substances within inhabited spaces. The second aspect concerns the use of local resources. The use of materials sourced from the surrounding territory reduces the energy required for transportation and enhances the value of locally available natural resources. This choice also strengthens the relationship between the building and its

geographical context, maintaining a material continuity between architecture and landscape. The third point relates to perceptual adaptability to the landscape. The chromatic and material qualities of stone allow buildings to visually integrate with the surrounding environment. This perceptual continuity favors a balance between natural and built landscapes, avoiding excessive contrasts with the territorial context. A fourth element concerns long-term durability. Numerous historical examples demonstrate the capacity of stone constructions to withstand time and atmospheric agents. The long service life of buildings represents a relevant factor also from a sustainability perspective, as it reduces the need for structural replacement over time. The fifth point concerns the possibility of material reuse. Stone elements can be recovered and reused in new construction interventions, extending the life cycle of the material and limiting the production of construction waste. This characteristic makes stone compatible with circular economy strategies applied to architecture. Finally, stone presents interesting bioclimatic performance. Thanks to its high thermal mass, the material is able to store heat and release it gradually, contributing to the stabilization of indoor temperatures and improving thermal comfort. This property can reduce the energy demand of buildings and promote more climatically efficient behavior.

Table 1. Sustainable Qualities of Stone in Contemporary Architecture.

Aspect	Description	Sustainable Contribution
Health reliability	Natural mineral material free from harmful emissions	Healthier indoor environments
Use of local resources	Use of stone sourced from the surrounding territory	Reduced transport energy and stronger territorial identity
Landscape adaptability	Visual integration through natural colours and textures	Balance between architecture and landscape
Long-term durability	Resistance to time and atmospheric agents	Reduced need for replacement and maintenance
Material reuse	Possibility of recovering and reusing stone elements	Reduction of construction waste and support for circular economy
Bioclimatic performance	High thermal mass capable of storing and releasing heat gradually	Improved thermal comfort and reduced energy demand

Direct observation of the territory through field surveys has highlighted how numerous stone architectures remain deeply integrated within the landscape context even today. However, many of these buildings are currently in conditions of abandonment and degradation, often progressively engulfed by vegetation and destined for a slow disappearance (Fig. 3). In many rural contexts, it is possible to observe buildings that were once an integral part of the agricultural landscape but now appear isolated and devoid of function. This condition highlights the need to recognize and enhance stone architectural heritage before it is permanently lost. The recovery of such constructions represents not only an act of conservation but also an opportunity to re-establish a more balanced

relationship between architecture, environment, and territory. The enhancement of stone architectures makes it possible to preserve a constructive memory that testifies to the relationship between communities, landscapes, and natural resources. Rethinking the role of this material within contemporary design therefore means restoring centrality to a building tradition capable of combining territorial identity, environmental quality, and cultural continuity. (D.L.)



Fig. 3. Rural stone building, Montemarano, Italy.

2 Building with Stones as Community Practice

Where stones were an integral part of the habitat, construction processes proceeded in harmony with local natural systems. People used to dig directly into the stone rocks or reuse river pebbles, as had been done for centuries along the coasts of Calabria, where circular connection also involved building construction tradition. The isolated location made it hard to use cut stones from a quarry. While the presence of torrents nearby, just underneath the villages, provided the stones to be used for wall construction with smooth surfaces because of a process of erosion and weathering due to the contact with running water.

Building with stones today tends to take on a meaning of artistic vocation for cmmunities as, in relation to the esthetic and integrative perceptive value of stone, people focus on how the material recovered on-site for construction contributes to establishing a strong sense of belonging between the building and the place where it stands. In internal rural areas, anchorage to small works with stones, apparently in continuity with the ground, has the effect of making habitats recognizable as distinctive places. So stone building processes enrich a design dimension made of connections in a practicable strategy also for the involvement of communities and we could even say that they consider working with stones a poetical craftsmanship. Artistic experiences tend to involve people in communities better than purely practical experiences. Enriching territories through creative artistic work is a good strategy for the involvement of communities and it leads to transversal effects on environments. Ecological aesthetics brings art inside territories. Applying this approach to a traditional technology, it is useful to rethink ecomuseum experiences, where the local approach has gained a high grade of community consensus. An emblematic conceptual and practical idea of creating effects

of interplay between people and territories is possible to be found in the first idea of "ecomuseum" that was defined by Georges Henri Rivière as "a mirror in which the local population views itself to discover its own image" (Rivière 1980). The ecomuseum experiences are still fundamental in this direction. Today there is "a strong worldwide movement where community museums and ecomuseums consider themselves and are recognized by the museum world and all heritage institutions as following the same principles and sharing objectives and practices for participatory and democratic heritage management at the local level" (De Varine 2017). An appropriate approach for masonry design with new significant structures is a complex environmental design issue. Any cohesive recovery involves an extension of scale both in the temporal dimension and the geographical one, focusing a network of components as agents capable of redefining the area under balanced economic, social, and geographical aspects. Now, to say the truth, consideration of people and life has always been part of the architectural project; it is its founding character. But it is only in the transition to a new systemic dimension that we identify, in a matrix of possibilities, interventions capable of actually connoting in a congruent way a close link between people and places. Stone recurrences in facades have the capability of leaving a stressful impression in mind with recurrences of typical elements; on the other side, we also have in mind specific local realities in which masonry constructions return as local characterized places, almost an identity character. This could seem like a contradiction: masonry constructive technologies are recurrent, but they always induce an adhesion to local identity in communities that recognize in these constructions an image of uniqueness. This double aspect of the question arises from the fact that local kinds of buildings are always connected to the large spectrum of environmental data, such as the height of the reliefs, the presence of rivers, the distance from the sea, the local stones, and the surrounding vegetation and cultivations, which are fundamental for specificity. Examples of new experimentation are made today with stones in new masonry buildings. The most emblematic examples can be considered Peter Zumthor's works with stones. His architecture with stone is perceived with all the senses, with an atmospheric involvement, by the tactile appearance of stones, and at the same time the effects of natural light on the surfaces. In his buildings the use of stones lets the building appeal like something in continuity with the landscape, as a whole natural and artificial continuity, like in the Vals Therme. A reference for building with stones today, moreover, must remain Mario Botta's experimentation with materials of quarries that were very close to the building site, with a general result in sustainable construction with minimum impacts. With a similar sustainable approach, today we observe the works by Tuñón Albornoz Arquitectos, with percentual congruence with the landscape and historical buildings. So the first principle to be implemented starting from these case studies for territorial regeneration is the research of coherence between local identity and new masonry architecture, inferred from the precise geographical and environmental adaptation to contexts. The second principle is correlated to the fact that a recovery project, in order to be really an instrument of territorial regeneration, should be put in a congruent network, recognizing a systemic and progressive value, not unique, in the dynamics of flexible correlations, with interventions that extend the effects of attraction beyond the strictly physical context. (F.M.)

3 Conclusions

The analysis developed in this study suggests that stone architecture may still represent a significant resource for contemporary sustainable design strategies, particularly in relation to the use of local materials, durability, reuse potential, and integration with the landscape. The analyzed case studies demonstrate how traditional construction practices developed in close relationship with territorial resources and local environmental conditions, generating architectures characterized by material continuity and climatic adaptation. At the same time, the field observations highlight the progressive abandonment of numerous stone buildings, revealing the risk of losing not only architectural heritage but also the traditional construction knowledge associated with it. From this perspective, the recovery and contemporary reinterpretation of stone architecture may contribute not only to the conservation of cultural heritage, but also to the development of design approaches more strongly rooted in environmental and territorial contexts, coherently with the principles of environmental sustainability and the responsible use of local resources. (D.L.)

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Clear Matter: Translucent Wood Bio-composites

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Abstract. Translucent Wood (TW) is a promising bio-based composite for low-carbon architectural applications, combining optical functionality with renewable material sourcing. Yet, current TW fabrication methods rely on synthetic polymer infiltration systems, limiting environmental sustainability and End-of-Life (EoL) circularity. The aim of the paper is to explore two alternative sustainable fabrication methods, *A* and *B*. Two infiltrants, water-soluble polyvinyl alcohol (PVA, 8 wt%) and modified starch (8 wt%), were selected for their refractive index compatibility with cellulose (n ≈ 1.49–1.52). Veneers of Norway spruce (*Picea abies*) in *Method-A* and balsa (*Ochroma pyramidale*) in *Method-B* were first delignified and subsequently infiltrated under vacuum, then consolidated by hot-pressing to 0.50–1.00 mm thick specimens. Two delignification routes were evaluated: (i) acidic delignification using peracetic acid and (ii) a sequential alkaline-bleaching route ($NaOH + H_2O_2$). Results from *Method A* showed that polymer properties, wood species and processing parameters strongly influence infiltration quality, interlaminar bonding and structural performance. Although PVA-based TW demonstrated relatively high tensile properties (≈140 MPa tensile strength and 15 GPa Young's modulus), the starch-based composites also exhibited promising mechanical properties (≈95 MPa and 5 GPa, respectively). Optical characterisation demonstrated that polymer type and laminate thickness significantly affect light transmittance, colour uniformity and gloss. Starch-infiltrated specimens reached 45% total transmittance at 0.50 mm thickness. Given the proof-of-principle scope of this study, the results indicate preliminary trends based on a limited specimen sample size. TW thus demonstrates strong potential as a high-performance bio-based material, with ongoing research focusing on scalability, durability and improved recyclability.

Keywords: Translucent Wood · Delignification · Biobased Polymer · Mechanical Strength · Light Transmittance

1 Introduction

The construction and operation of buildings account for nearly 39% of carbon dioxide emissions and is therefore under unprecedented scrutiny to transition to more energy-efficient design and use strategies [1]. Transparent materials are widely used in the built environment, where they hold a strong influence on energy efficiency, daylighting and structural capacity. This has led to increasing research interest in transparent

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materials that can satisfy optical requirements while also providing mechanical robustness and improved thermal performance. Within this context, Translucent Wood (TW) has emerged as an engineered wood-based bio-composite that integrates these properties within a single material [2]. It is fabricated by removing lignin from wood and infiltrating the porous cellulose matrix with a refractive index-matched polymer to minimize light scattering [3]. Depending on the wood species, TW exhibits densities from 0.16 g/cm^3 (balsa) to 0.68 g/cm^3 (ash), making it lighter than conventional translucent materials [4]. TW composites retain the hierarchical structure of wood, combining optical functionality with low thermal conductivity and high fracture toughness [2].

However, the upscaling of TW composites from laboratory to application remains constrained by fabrication complexity, cost and limited production scalability [4, 5]. Moreover, dependence on synthetic infiltrants undermines circularity, motivating the development of bio-based infiltration systems. Accordingly, this study investigates the fabrication of multilayer TW bio-composites and evaluates their preliminary mechanical and optical performance using two infiltrants with a compatible refractive index ($n \approx 1.49–1.52$): polyvinyl alcohol (PVA, 8 wt%) and modified starch (8 wt%). Norway spruce veneers were delignified using an acidic route (*Method A*), whereas balsa veneers were delignified using a sequential alkaline-bleaching route (*Method B*), followed by vacuum infiltration and hot-press consolidation. The influence of delignification route, infiltrant type and laminate thickness is assessed.

Overall, this research positions TW composites as promising materials for architectural applications from a sustainability perspective while identifying key challenges related to scalability, durability and End-of-Life (EoL) recyclability. As a proof-of-principle study, these findings indicate preliminary trends and the limited number of specimens constitutes a primary limitation.

2 Experimental Section

2.1 Materials

Wood veneers of Norway spruce (*Picea abies*), d = 0.90 mm/ply and balsa (*Ochroma pyramidale*), d = 1.50 mm/ply, were used as lignocellulosic substrates and sourced from a commercial supplier (hout-fineer.nl). Poly (vinyl alcohol) (PVA, 88% hydrolysed, Mw ≈ 88 000, Sigma-Aldrich) and modified starch (Collabond 8017 IQ, Agrana Stärke GmbH, Austria) were employed as infiltration polymers. Hydrogen peroxide (H_2O_2), glacial acetic acid (CH_3COOH), sodium hydroxide (NaOH), and sodium sulfite (Na_2SO_3) were obtained from Sigma-Aldrich and used as received. All aqueous solutions were prepared using deionized (DI) water.

2.2 Methods

Two fabrication routes were developed to assess how delignification and infiltration affect multilayer TW microstructure and performance. Due to the limited sample size, the methods focused on comparing fabrication feasibility and indicative material behaviour.

In *Method A*, Norway spruce veneers were delignified using a peracetic acid system formed from hydrogen peroxide and acetic acid (1:1 v/v) under controlled heating (~80 °C) until sufficient lignin removal was achieved while preserving fibre integrity. Veneers were rinsed repeatedly with DI water until they reached pH 7. Polymer solutions of 8 wt% aqueous PVA and 8 wt% modified starch were prepared under heating (~90 °C) and magnetic stirring (500 rpm) until fully dissolved. Delignified veneers were vacuum impregnated to remove trapped air and promote polymer penetration into cell lumina. Laminates (2–6 plies) were then oven-dried (~80 °C, 1 h) and hot-pressed using staged temperature-pressure cycles (80–140 °C, ~10 bar) with cooling under pressure to improve interlaminar bonding and dimensional stability (Fig. 1).

Method B employed an alkaline-oxidative preparation route to better preserve the cellulose fibres and hierarchical structure. Balsa veneers were treated in aqueous NaOH (2.5 mol L^{-1}) and Na_2SO_3 (0.4 mol L^{-1}) at ~105 °C, rinsed until they reached pH 7 and bleached in aqueous H_2O_2 (2.5 mol L^{-1}). Impregnation was performed while the veneers remained wet to prevent pore collapse. Polymer solutions (8 wt% PVA or modified starch) were prepared (~90 °C) and infiltration was conducted using repeated vacuum cycles (~2 mbar, 3 × 45 min) until gas evolution ceased. Samples were then dried gradually at 60 °C for ~48 h, allowing slow evaporation and progressive polymer solidification (Fig. 1).



Fig. 1. TW specimens fabricated using *Methods A* and *B*. From left to right: 8 wt% PVA-infiltrated Norway spruce (*Method A*); 8 wt% modified starch-infiltrated Norway spruce (*Method A*); and 8 wt% PVA-infiltrated delignified balsa (*Method B*).

2.3 Mechanical Characterization

The objectives of the mechanical tests on *Method A*-specimens were to evaluate how infiltration with different polymer types, 8 wt% modified starch and 8 wt% PVA, affect the mechanical behaviour of polymer-infiltrated delignified wood to assess its potential suitability for building applications. The study also compared the mechanical behaviour of 2-ply and 6-ply laminated veneers and examined how specimen thickness affects the mechanical properties of translucent wood through changes in polymer distribution and interlayer bonding. The results should be interpreted as indicative trends rather than definitive quantitative values.

Tensile and three-point bending were conducted using a Zwick Z010 Universal Testing Machine. The 10 specimens per test had dimensions of 15 mm (W) × 150 mm (L) × 0.50–1.00 mm (t). Tensile tests were performed with a 10 kN tensile grip at a displacement rate of 5 mm/min and a 50 mm grip opening. US 80-grade sandpaper was used on the grips to prevent slippage at the clamping ends. Three-point bending tests were carried out using a bending fixture with a 40 mm deformation limit, span of 50 mm and the displacement rate of 10 mm/min.

2.4 Optical Characterization

For both optical tests, *Method-A* specimens were evaluated, the equipment was initially calibrated and the derived results should be interpreted as indicative rather than definitive quantitative values. Luminous transmittance (Tv) and spectral transmittance T(λ) were measured under diffused daylight (south-facing window, 1st floor, BK building, Delft, 20/10/2025, 15:40–15:50) and a warm LED (~2700 K) using an Illuminance Spectrophotometer (IS). Eqs. (1) and (2) were used to compute Tv and T(λ) from illuminance (E_v) and Spectral Power Distribution (SPD) values, respectively. Fig. 2 illustrates the optical test setup.

$$\mathrm{Tv}\ (\%) = 100 \times \frac{\mathrm{Ev}_{\mathrm{sample}}}{\mathrm{Ev}_{\mathrm{blank}}} \tag{1}$$

$$\mathrm{T}(\lambda)\ (\%) = 100 \times \frac{\mathrm{SPD}_{\mathrm{sample}(\lambda)}}{\mathrm{SPD}_{\mathrm{blank}(\lambda)}} \tag{2}$$

TW surface appearance was assessed by measuring diffuse and specular reflectance, colour and gloss with a Reflectance Spectrophotometer (RS). Two measurements per specimen were taken on a flat, non-reflective, white background and averaged (Fig. 2). Colour was reported in CIE LCh° coordinates after averaging in L*a*b* space, while gloss values (GU) were averaged directly.

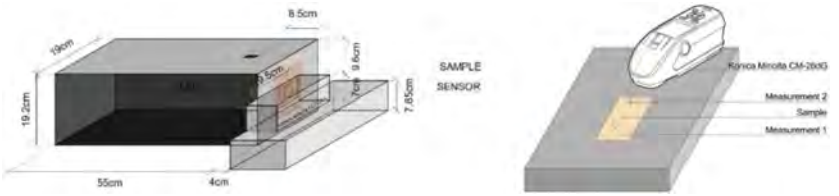


Fig. 2. Optical test setups. From left to right: Konica Minolta CL-500A illuminance spectrophotometer (360–780 nm, 1 nm pitch) used for transmittance measurements, showing enclosure geometry, sensor, and sample positions; Konica Minolta CM-26dG reflectance spectrophotometer (d:8°, 360–740 nm, 60° gloss sensor; MAV 10 × 7 mm) used for reflectance measurements, showing the setup and specimen measurement positions.

3 Results and Discussion

3.1 Microscopy

Microscopy of *Method A*-specimens was conducted on embedded cross-sections (Keyence VK-X1000, ~20×) and surface topography (Keyence VR Series, ~80×). Results showed heterogeneous polymer impregnation (partially filled lumina, interfacial voids), local fibre misalignment and micro-cracks in the cell-wall network, consistent with reduced translucency during the initial visual inspection. These preliminary findings guided the optimisation of fabrication *Method B* (Fig. 3).

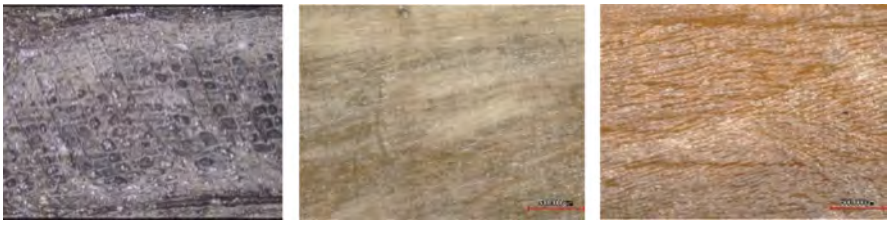


Fig. 3. Microscopic Characterisation. From left to right: cross-section of starch-infiltrated wood (20×); surface morphology (~80×); and PVA-infiltrated specimen showing local fibre misalignment (~80×).

3.2 Mechanical Characterisation

The tensile strength and flexural modulus were evaluated as functions of Norway spruce specimen thickness (2-ply, 6-ply) and polymer type (PVA, starch). PVA-infiltrated specimens exhibited higher tensile strength than starch-infiltrated specimens at equal ply thickness, reflecting improved stress transfer and stronger cellulose fibre-polymer interfacial bonding. Greater ply thickness increased stiffness but not tensile strength, likely due to internal defects or imperfect bonding. Tensile strength ranged from 80–140 MPa (PVA-based) and 60–95 MPa (starch-based). Subject to flexure, starch-infiltrated specimens showed pronounced delamination and shear cracks, indicating weak interlaminar adhesion. PVA-infiltrated specimens exhibited no delamination, reflecting stronger fibre-polymer adhesion. PVA-infiltrated specimens exhibited higher flexural strength and modulus. Starch-based specimens were slightly more ductile. Flexural moduli ranged from 7–16 GPa for PVA and 2–8 GPa for starch-infiltrated specimens. Mechanical tests indicated that polymer type governs the mechanical performance of TW composites. Overall, the results align with previous TW studies, indicating that mechanical performance is primarily determined by fibre-polymer bonding. In this preliminary comparison, PVA appears to be the more mechanically reliable infiltrant.

3.3 Optical Characterisation

At equal thickness modified starch- showed higher T_v values than PVA- infiltrated specimens under both illuminants. Increasing laminate thickness reduced T_v values for both

systems, with PVA exceeding modified starch. Relative to the warm LED, daylight yields higher peak wavelength (λ_{peak}), with the greatest increase observed for the thicker specimens (Table 1).

Table 1. IS (Cl-500A): T_v and λ_{peak} values of the most indicative specimens.

Polymer, Thickness	T_v (LED)	T_v (Day)	λ_{peak} (LED)	λ_{peak} (Day)
PVA, 0.50 mm	28.85%	22.27%	619 nm	668 nm
PVA, 0.71 mm	16.32%	12.62%	620 nm	667 nm
Starch, 0.50 mm	45.25%	33.69%	614 nm	639 nm
Starch, 0.74 mm	13.16%	8.02%	623 nm	673 nm

All specimens exhibited warm yellow hues and matte surfaces. For both polymers, lower thickness (t) generally resulted in higher chroma, with the modified starch specimen at $t = 0.50$ mm showing the highest value. In the PVA series, lightness increased with thickness, reaching a maximum at $t = 0.71$ mm, whereas the opposite trend was observed for the modified starch series (Table 2).

Table 2. RS (CM-26dG): Mean CIE LCh° values (SCE and SCI) and gloss (60°).

Polymer, Thickness	L* (SCE)	L* (SCI)	C* (SCE)	C* (SCI)	h° (SCE)	h° (SCI)	Mean GU
PVA, 0.50 mm	51.94	57.10	37.68	41.46	61.79	65.95	4.74
PVA, 0.71 mm	77.14	77.56	28.18	28.01	79.08	79.10	5.64
Starch, 0.50 mm	64.12	64.58	43.41	43.10	70.12	70.12	5.60
Starch, 0.74 mm	62.69	63.19	34.59	34.33	71.81	71.82	4.52

In comparison with conventional translucent materials, TW enables diffuse daylight transmission while maintaining visual privacy, positioning it between opaque timber products and fully transparent glazing systems.

4 End-of-Life (EoL) Considerations and Scalability

Circularity and industrial feasibility are critical for establishing TW as a sustainable material. The environmental comparison presented in this research is addressed at the level of infiltrant chemistry and EoL potential. Unlike epoxy-based transparent wood

systems, whose irreversible thermosetting networks limit reprocessing, recyclability and biodegradability [6, 7], the PVA- and starch-based systems explored here may offer circular recovery pathways. Reported enzymatic and fungal biodegradation mechanisms for PVA [8], together with soil biodegradation of starch-based materials [9], suggest that these infiltrants could support more environmentally compatible EoL scenarios. More broadly, compared with conventional transparent materials such as polyethylene (PE), TW has been reported to show lower overall EoL environmental impacts, supporting its potential as a safer bio-based alternative to petroleum-derived transparent materials [10]. However, this comparison remains a preliminary material-level assessment rather than a full quantitative Life Cycle Assessment (LCA).

The long-term viability of TW depends on scalability, with delignification identified as the primary bottleneck. This fabrication stage is both chemically and energy intensive, requiring strict process control to prevent cellulose fibre degradation and preserve structural integrity. A recent study has investigated biological delignification as a more gentle, low-energy alternative using the white-rot fungus, removing up to 65 wt% of lignin over several weeks under controlled humid conditions [11]. Furthermore, titanium dioxide (TiO_2) nanoparticle coatings have been shown to improve UV stability and moisture resistance without reducing transparency, providing opportunities for more durable and waterproof translucent wood composites [12].

5 Conclusions

The research developed TW laminates fabricated from softwood (Norway spruce) and hardwood (balsa) with 2-ply and 6-ply configurations. Two polymer infiltration systems, 8 wt% PVA and 8 wt% modified starch, were selected based on their compatible refractive index ($n \approx 1.49–1.52$) with cellulose. It was found that polymer type and fabrication method significantly influence infiltration quality, interfacial bonding and the resulting optical and mechanical properties. The challenge of optimising polymer infiltration in bio-derived translucent wood bio-composites is prominent. Specimens infiltrated with PVA exhibited greater strength and stiffness than starch-based specimens. Optical tests revealed that polymer type and specimen thickness strongly influence light transmittance and colour, while both systems consistently exhibited matte surfaces. Starch-based specimens showed higher Tv values and decreasing lightness with increasing thickness, whereas PVA-based specimens showed the opposite trend. Chroma decreased with increasing thickness in both systems, and all specimens exhibited warm yellow hues.

The main takeaways show that although multilayer TW exhibits promising mechanical and optical performance, further optimisation is needed to enhance repeatable fabrication processes and scalability. Looking ahead, future work will focus on further testing, including impact, thermal and fire performance characterisation, supported by LCA, to provide insights into environmentally friendly delignification methods and scalable fabrication strategies.

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Sustainable Reinforcement of Asphalt Concrete Surface Layers: A Comparative Study of Mild NaOH and TEOS Surface Treatments for Jute Fibres

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Abstract. The increasing demand for durable and sustainable infrastructure requires innovative approaches to improve asphalt mixture performance. This study investigates the use of bio-based jute fibres as reinforcement in asphalt concrete for surface layers (AC_{surf} 16+), with particular focus on fibre dosage and surface treatment using NaOH and tetraethyl orthosilicate (TEOS).

A conventional 50/70 paving-grade bitumen was used for the reference and fibre-reinforced mixtures, while a polymer-modified bitumen (PMB) mixture was included as a control for performance comparison. The evaluated properties included air voids, stiffness (indirect tensile test, IT-CY), moisture susceptibility, and crack propagation resistance assessed using the semi-circular bending (SCB) test.

The results show that jute fibres can improve selected mechanical properties, particularly crack resistance, with performance strongly influenced by fibre characteristics and surface treatment. TEOS-treated fibres demonstrated enhanced interaction with the bituminous matrix, leading to improved resistance to crack propagation compared to untreated fibres.

These findings indicate that treated bio-based fibres represent a promising sustainable alternative or complementary solution to conventional polymer modification in asphalt mixtures.

Keywords: Asphalt concrete · jute fibres · TEOS · crack resistance · sustainable materials

1 Introduction

Bitumen mixtures are used in the most prevalent type of paved roads worldwide. Mitigating common structural damage mechanisms, such as permanent deformation and crack propagation, can help prolong their service life and reduce significant economic costs. Asphalt binder modification and the use of additives are among the most adopted strategies to improve the relatively low tensile strength and overall performance of asphalt mixtures. Among these additives, various types of fibres have gained considerable attention due to their high tensile strength, modulus, and ability to enhance ductility.

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Fibres are among the most widely used additives in asphalt mixtures, and their application has been extensively studied. Recently, they have attracted renewed attention in the road construction industry due to their wide variety and their ability to significantly enhance mixture performance for specific applications. One of the main shortcomings of asphalt mixtures is their low tensile strength, which leads to crack initiation and propagation. In this context, the use of fibres with high tensile strength represents an effective solution. Once incorporated into the mixture, fibres act as reinforcing elements, increasing cohesion and reducing susceptibility to reflective and fatigue cracking, while also improving resistance to permanent deformation. Additionally, fibres can function as stabilizing additives that limit binder runoff (drain-down), particularly in SMA and porous asphalt mixtures, which are typically rich in binder. In this role, fibres behave similarly to very fine aggregate, helping to reduce binder bleeding on the pavement surface. Overall, fibre addition can positively influence the viscoelastic behaviour of asphalt mixtures, increase dynamic modulus, and improve resistance to rutting. Furthermore, fibres contribute to enhanced resistance to cyclic freezing and thawing, as well as to crack initiation and propagation [1].

The performance of fibre-reinforced asphalt mixtures is largely governed by the quality of the fibre–bitumen interphase, which controls stress transfer, crack-bridging efficiency, and durability under environmental loading.

This paper explores the possibility of using a bio-based alternative to commercially available synthetic fibres. Jute fibres with a length of 20 mm were used at contents of 0.1%, 0.2%, and 0.3% by weight, combined with different surface treatments to improve chemical compatibility. Air voids, stiffness (IT-CY), resistance to crack propagation (SCB), and moisture susceptibility were evaluated.

2 Materials and Methods

The effect of bio-based fibres and their surface treatment was evaluated using asphalt concrete for surface layers AC_{surf} 16+ with a nominal maximum aggregate size (NMAS) of 16 mm, corresponding to ACO 16+ according to ČSN 73 6121:2019.

Six mixtures with identical aggregate gradation were produced. A conventional paving-grade bitumen 50/70 was used for the reference mixture and all fibre-reinforced mixtures. A polymer-modified bitumen (PMB 25/55–60) mixture without fibres was included as a control for performance comparison. Mixing and compaction temperatures were 150 °C for 50/70 mixtures and 160 °C for the PMB mixture.

Jute fibres with a length of 20 mm were used as three-dimensional reinforcement. Fibre contents of 0.1%, 0.2%, and 0.3% by total mixture weight were investigated. The inherently rough and heterogeneous surface of bio-based fibres promotes mechanical interlocking at the fibre–bitumen interface. Surface treatment of fibres was applied to improve stress transfer and physicochemical compatibility with the bitumen matrix. Mild alkaline treatment was performed by immersing pre-cut jute fibres in a 1% NaOH solution for 24 h. The fibres were subsequently rinsed with demineralised water until neutral pH (6–8) was achieved using citric acid, followed by a final rinse and drying at 50 °C for 12 h. TEOS treatment was applied to NaOH-treated fibres to enhance thermal stability and interfacial bonding. The detailed procedure follows [2].

Asphalt mixtures were prepared and compacted according to ČSN 73 6121:2019 and EN 12697–30 using a Marshall impact compactor. Specimens for stiffness testing (IT-CY) were compacted with 2 × 50 blows, while specimens for moisture susceptibility (ITSR) were compacted with 2 × 25 blows. For SCB testing, cylindrical specimens were cut along the compaction axis to obtain semi-circular specimens. A notch of 10 mm was introduced at mid-span.

An overview of mixtures is presented in the Table 1.

Table 1. AC_{surf} 16+ (ACO 16+) mixtures produced and tested

Mixture's label	Binder	Description
REF	50/70	Control mixture without additives
1		0.1% by weight 20 mm jute fibres (1% NaOH)
2		0.2% by weight 20 mm jute fibres (1% NaOH)
3		0.3% by weight 20 mm jute fibres (1% NaOH)
2_T		0.2% by weight 20 mm jute fibres (NaOH+TEOS)
PMB	PMB 25/55–60	Second control mixture with modified bitumen

To evaluate the performance of asphalt mixtures, a selection of laboratory tests was performed: **(i)** air voids according to EN 12697–8; **(ii)** determination of stiffness according to EN 12697–26, Annex C: IT-CY test method; **(iii)** resistance to crack propagation according to ČSN EN 12697–44 with a modified procedure: loading rate (2.5 mm/min), length of test specimens 100 mm (IT-CY based) [3]; **(iv)** moisture and freeze-thaw susceptibility (ITSR) according to EN 12697-12 and the water + one freeze cycle according to AASHTO T283 (modified procedure used at CTU in Prague [4]).

Resistance to crack propagation was evaluated using fracture energy parameters derived from SCB load–displacement curves. The pre-peak fracture energy $G_{f,pre}$, post-peak fracture energy $G_{f,post}$ and total fracture energy $G_{f,tot}$ [5], flexibility index (FI) [5], and crack resistance index (CRI) [6] were used to characterize crack propagation behavior. These parameters describe, respectively, the energy required for crack development, the post-peak deformation capacity, and the overall resistance to crack propagation derived from SCB load–displacement response.

3 Results and Discussion

3.1 Air Voids

The air voids of the mixtures are summarised in Table 2. None of the mixtures satisfied the control testing range of 2.0–5.0% for AC_{surf} 16+ according to ČSN 73 6121:2019.

As expected, the incorporation of fibres led to an increase in air voids, with mixture 3 (0.3% fibres) exhibiting the highest values. This trend can be attributed to the reduced workability and hindered compaction caused by the presence of fibres, which can form local agglomerations and disrupt aggregate packing.

Mixtures without fibres (REF and PMB) exhibited the highest bulk density, indicating more efficient compaction and aggregate interlock. In contrast, fibre-reinforced mixtures showed reduced bulk density due to the inclusion of low-density, deformable fibre structures.

The TEOS-treated mixture (2_T) showed a lower air voids compared to the corresponding NaOH-treated mixture (2), suggesting improved compactability. This behaviour may be associated with changes in fibre surface characteristics, such as increased stiffness or reduced fibrillation, leading to less interference with aggregate packing. These results indicate that fibre content and surface treatment significantly influence mixture volumetrics, which may subsequently affect mechanical performance and durability.

Table 2. Air void of AC_{surf} 16+ mixtures

Mix	Bulk density [g.cm^{-3}]	Maximum density [g.cm^{-3}]	Air voids [%]
REF	2.300	2.432	5.4
1	2.274	2.412	5.7
2	2.258	2.425	6.9
3	2.260	2.430	7.0
2_T	2.276	2.410	5.6
PMB	2.308	2.383	5.7

3.2 Stiffness (IT-CY)

The stiffness modulus was determined on Marshall specimens at 0 °C, 15 °C, 27 °C, and 40 °C. The results are summarised in Table 3.

The PMB mixture exhibited the highest stiffness across the entire temperature range, confirming the effectiveness of polymer modification in enhancing the elastic response of asphalt mixtures. It also showed relatively low thermal susceptibility (TS), indicating a more balanced stiffness response with temperature.

The incorporation of fibres influenced stiffness depending on both fibre content and surface treatment. In general, fibre-reinforced mixtures did not exhibit an increase in stiffness compared to the reference mixture at elevated temperatures (27 °C and 40 °C). On the contrary, higher fibre contents tended to reduce stiffness at these temperatures, which may be associated with increased air voids and reduced load transfer efficiency within the mixture. A comparison between mixtures 2 (NaOH-treated fibres) and 2_T (NaOH + TEOS-treated fibres) highlights the effect of surface treatment. The NaOH-treated fibres resulted in lower stiffness and lower TS values, indicating a more temperature-tolerant and potentially more ductile response. In contrast, the TEOS-treated fibres led to higher stiffness at intermediate temperatures but also the highest TS values, suggesting increased sensitivity to temperature variations.

The increased thermal susceptibility observed in the TEOS-treated mixture may indicate a stiffer but less adaptable material behaviour, which could increase the risk

of thermally induced cracking at low temperatures. This behaviour suggests that while TEOS treatment enhances fibre–matrix interaction, it may also promote a more brittle response under thermal loading.

Overall, the results demonstrate that fibre surface treatment plays a key role in controlling the thermo-mechanical response of asphalt mixtures, with a trade-off between stiffness enhancement and thermal adaptability.

Table 3. Stiffness modulus (S_m [MPa]) of AC_{surf} 16+ mixtures. Thermal susceptibility (TS) is on the right side. Standard deviation σ written in Italic is next to the stiffness values.

	0 °C		15 °C		27 °C		40 °C		TS	
Mix	S_m	σ	S_m	σ	S_m	σ	S_m	σ	*S0/S27*	*S0/S40*
REF	16 283	*1 024*	6 845	*564*	3 071	*200*	1 203	*103*	5.3	13.5
1	15 653	*917*	7 178	*237*	2 889	*90*	956	*27*	5.4	16.4
2	12 277	*342*	6 842	*210*	2 902	*155*	1 007	*42*	4.2	12.2
3	13 689	*694*	6 593	*346*	2 456	*46*	791	*27*	5.6	17.3
2_T	16 470	*570*	8 013	*336*	2 576	*75*	924	*66*	6.4	17.8
PMB	18 476	*482*	9 652	*534*	3 838	*172*	1 480	*29*	4.8	12.5

3.3 Resistance to Crack Propagation (SCB)

Resistance to crack propagation was evaluated using SCB specimens tested at 0 °C. The specimen diameter was reduced from the standard 150 ± 1 mm to 101 ± 1 mm, and the loading rate was decreased from 5.0 mm/min to 2.5 mm/min to obtain a more stable and detailed load–displacement response. The results are presented in Table 4.

Table 4. Selected parameters of SCB test at 0 °C. $K_{I,c}$ is the critical value of resistance to crack propagation (fracture toughness). Flexibility index (FI) and Crack resistance index (CRI) are on the right side. Standard deviation σ is written in Italic.

	$K_{I,c}$		$G_{f,pre}$		$G_{f,post}$		$G_{f,tot}$		FI		CRI	
Mix	[N/mm$^{3/2}$]	σ	[J/m^2]	σ	[J/m^2]	σ	[J/m^2]	σ	[J/m^2]	σ	[−]	σ
REF	28.1	*3.1*	864	*292*	443	*185*	1 307	*417*	23	*8*	228	*52*
1	27.1	*4.4*	1 102	*457*	504	*85*	1 606	*509*	39	*25*	290	*68*
2	28.6	*2.6*	792	*130*	482	*125*	1 274	*185*	38	*18*	237	*68*
3	29.1	*3.4*	1 049	*411*	682	*239*	1 731	*577*	28	*11*	254	*42*
2_T	29.7	*3.3*	1 203	*448*	530	*93*	1 733	*526*	24	*15*	281	*60*
PMB	39.6	*2.2*	1 483	*243*	256	*77*	1 739	*212*	8	*2*	228	*19*

Observing Table 4, the PMB mixture exhibited the highest fracture toughness $K_{I,c}$, confirming its superior resistance to crack initiation. However, fibre-reinforced mixtures

demonstrated comparable or higher total fracture energy $G_{f,tot}$, indicating improved resistance to crack propagation.

The increase in fracture energy observed in fibre-reinforced mixtures is primarily associated with enhanced post-peak behaviour, as reflected by higher values of $G_{f,post}$. This suggests the activation of fibre-bridging mechanisms, where fibres transfer stresses across the crack faces and delay crack propagation.

Among the investigated mixtures, increasing fibre content generally led to higher total fracture energy, with mixture 3 (0.3% fibres) showing a notable improvement compared to the reference mixture. This indicates that a higher fibre concentration promotes more effective crack-bridging; however, this effect must be considered in relation to increased air void content and potential reductions in stiffness.

The influence of fibre surface treatment is evident when comparing mixtures 2 (NaOH-treated fibres) and 2_T (NaOH + TEOS-treated fibres). The TEOS-treated mixture exhibited higher total fracture energy and fracture toughness, suggesting improved fibre–matrix interaction. This behaviour is likely associated with increased interfacial bond strength, resulting in greater resistance to fibre pull-out and more efficient stress transfer during crack propagation.

In terms of flexibility index (FI), fibre-reinforced mixtures showed significantly higher values compared to the PMB mixture, indicating a more gradual post-peak response and improved deformation capacity. Conversely, the PMB mixture exhibited low FI values, reflecting a more brittle failure behaviour despite its high fracture toughness. The crack resistance index (CRI) showed consistent improvements in fibre-reinforced mixtures compared to the reference mixture, further confirming the beneficial effect of fibres on crack resistance.

Overall, the results demonstrate that fibre reinforcement primarily enhances crack propagation resistance rather than crack initiation resistance, with the effectiveness strongly dependent on fibre content and surface treatment. This behavior suggests a transition from a matrix-dominated fracture mechanism in the reference mixture to a fibre-bridging-dominated mechanism in fibre-reinforced mixtures.

3.4 Moisture and Freeze-Thaw Susceptibility

The results of moisture and freeze–thaw susceptibility are presented in Table 5. Mixtures 1 and 3 were excluded from this test.

The reference mixture (REF) and the NaOH-treated fibre mixture (2) exhibited comparable indirect tensile strength ratio (ITSR) values, suggesting that the mild alkaline treatment had no pronounced effect on moisture resistance under the applied test conditions.

In contrast, the TEOS-treated mixture (2_T) showed lower ITSR values, particularly after freeze–thaw conditioning, indicating a higher sensitivity to freeze-related damage. One possible explanation is that the surface modification altered the fibre–matrix interface in a way that reduced resistance to water ingress or to stress induced by conditioning cycle. The PMB mixture exhibited the highest indirect tensile strength (ITS) values in both the dry and conditioned states, confirming its superior absolute strength level under the tested conditions. Nevertheless, none of the evaluated mixtures satisfied the minimum ITSR requirement of 80% after conditioning according to ČSN 73 6121:2019.

Under moisture conditioning without freeze–thaw cycling, only the reference mixture slightly exceeded this threshold, whereas the remaining mixtures remained below it. The generally lower ITSR values, including those of the PMB mixture, may also be associated with the relatively high air void content, which suggests that further optimisation of the mixture design would be appropriate.

The lower resistance to freeze–thaw conditioning observed for the TEOS-treated fibres suggests that improvements in selected mechanical properties and crack propagation resistance may be accompanied by reduced durability under moisture exposure. These findings highlight the importance of balancing interfacial strengthening with long-term environmental stability when designing fibre-reinforced asphalt mixtures.

Table 5. Moisture and freeze-thaw susceptibility results. Indirect tensile strength (ITS) is in MPa. Standard deviation σ is written in Italic.

	dry		f + t			wet		
Mix	ITS	σ	ITS	σ	ITSR	ITS	σ	ITSR
REF	1.46	*0.05*	1.08	*0.05*	74%	1.18	*0.02*	81%
2	1.46	*0.02*	1.10	*0.05*	76%	1.10	*0.12*	75%
2_T	1.39	*0.01*	0.84	*0.03*	61%	1.08	*0.03*	78%
PMB	2.08	*0.06*	1.52	*0.05*	73%	1.61	*0.04*	77%

4 Conclusion

Six AC_{surf} 16+ asphalt mixtures were investigated to evaluate the influence of bio-based jute fibres and their surface treatment on volumetric and mechanical properties.

The results showed that fibre incorporation significantly affects mixture behaviour, with increasing fibre content leading to higher air void content and reduced compactability. This effect must be carefully considered, as it can influence both mechanical performance and durability.

Fibre reinforcement primarily enhanced resistance to crack propagation rather than crack initiation. This was demonstrated by increased fracture energy and flexibility index values, indicating improved post-peak behaviour associated with fibre-bridging mechanisms.

Surface treatment of fibres played a key role in controlling mixture performance. Mild NaOH treatment resulted in a more balanced thermo-mechanical response, while TEOS-treated fibres exhibited improved fracture resistance and interfacial interaction with the bituminous matrix. However, TEOS treatment also led to increased thermal susceptibility and reduced moisture resistance, indicating a trade-off between mechanical performance and environmental durability.

Although the PMB mixture showed superior stiffness and crack initiation resistance, fibre-reinforced mixtures achieved comparable fracture energy levels, suggesting that bio-based fibres can serve as a promising sustainable alternative or complementary solution in asphalt mixtures.

Overall, the performance of fibre-reinforced asphalt mixtures is strongly governed by the fibre–bitumen interphase, highlighting the importance of surface treatment in optimising both mechanical behaviour and durability.

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Upcycling Ceramic Waste into Additively Manufactured Acoustic Components for Circular Construction

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Abstract. This paper examines the architectural upcycling of post-consumer ceramic waste through a material-driven and digitally informed research framework for additively manufactured acoustic components. A 3D-printable ceramic composite was developed, using locally sourced fired ceramic waste, virgin clay, and bio-based binders, and turned into a performance-driven architectural element. Through systematic engineering, eleven paste formulations were investigated for their printability, porosity, shrinkage, and mechanical performance. Results identify a maximum recycled ceramic content of 40%, surpassing the 35% waste fraction reported for extrusion-based ceramic additive manufacturing. A fixed, dosage of methylcellulose ensured comparability across formulations and isolated bio-binder effects. Reduced firing shrinkage, and mechanical performance on par with virgin clay reference mixtures were achieved, while higher waste fractions exhibited increased porosity and reduced structural integrity. In parallel, frequency-driven digital workflows and multi-objective optimization were employed to create site-specific Helmholtz Resonator geometries compatible with the ceramic composite. Additive manufacturing enables fabrication of bespoke resonator arrays while maintaining material efficiency and circular value retention. Preliminary laboratory testing confirms the resonator concept and highlights the influence of porosity and firing shrinkage on acoustic performance. By integrating waste-derived ceramic composites with digitally informed, performance-driven fabrication, this project demonstrates that architectural components with quantified mechanical and acoustic performance can be produced from ceramic waste beyond existing additive processing capabilities.

Keywords: Ceramic waste · Bio-based binders · Additive manufacturing · Parametric design · Sound absorption · Circular construction

1 Introduction

The construction industry faces two growing challenges: the underutilization of ceramic waste streams and increasing exposure to urban noise pollution.

Exposure to environmental noise pollution has been identified as a significant risk to public health. The European Environment Agency reports that exposure to road, rail,

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aircraft, and industrial noise contributes to ischemic heart disease, cognitive impairment in children, sleep disturbance, and tinnitus [1]. In Amsterdam, many outdoor spaces experience noise levels exceeding 55 dB and are therefore classified as high-noise areas under the EU Environmental Noise Directive [2].

To address low-frequency noise, Helmholtz Resonators present a promising solution. A Helmholtz resonator consists of an enclosed cavity attached to the exterior through a narrow neck, absorbing sound at a specific resonant frequency [6, 9].

At the same time, the construction sector generates substantial quantities of ceramic waste that remain largely underutilized. Ceramic products such as tiles, sanitaryware, and tableware are widely used due to their durability, chemical stability, and resistance to environmental degradation. However, these same properties make them difficult to recycle once discarded. As a result, ceramic waste is frequently downcycled into low-grade applications such as road base or disposed of in landfills, representing a missed opportunity for circular material reuse within the construction industry [3].

Recent research has explored the use of recycled ceramics in construction materials and additive manufacturing. However, integration of recycled ceramic composites with acoustically tuned architectural components remains largely unexplored. Limited research has investigated transforming recycled ceramic waste into additively manufactured acoustic systems capable of addressing site-specific noise conditions [4, 8].

This research investigates whether post-consumer ceramic waste can be incorporated into a 3D-printable ceramic composite suitable for the fabrication of acoustically tuned Helmholtz resonator modules. Through material experimentation, digital acoustic optimization, and additive manufacturing prototyping, the study evaluates the feasibility of transforming ceramic waste into modular sound-absorbing architectural elements. The research contributes a high-recycled-content ceramic composite (up to 40%) exceeding current additive manufacturing limits, a validated workflow integrating material development with parametric acoustic design, and a scalable approach for producing performance-driven acoustic components from waste.

2 Materials and Methods

The research followed a material-driven methodology integrating recycled material development with acoustic form optimization. Two parallel streams were conducted: the development of a 3D-printable ceramic composite incorporating post-consumer waste, and the parametric design of acoustically tuned Helmholtz resonators. These were combined through additive manufacturing to fabricate and evaluate prototype acoustic modules. The study evaluates both material feasibility for extrusion-based printing and acoustic performance. Mechanical, physical, and acoustic testing were conducted.

2.1 Material Preparation and Paste Formulation

Post-consumer ceramic waste was sourced locally and processed into powder through crushing, grinding, and sieving. Two particle size fractions ($<$0.125 mm and $<$ 0.063 mm) were retained to improve homogeneity and extrusion stability. Virgin

clay provided plasticity and cohesion, while methylcellulose was added as a rheology modifier to improve extrusion stability and prevent phase separation. Water content was adjusted to achieve suitable rheology, and mixtures were mechanically homogenized. Eleven formulations containing 0–40% recycled ceramic powder were developed and evaluated through extrusion and small-scale printing trials focusing on extrusion continuity, layer adhesion, and structural stability.

2.2 Additive Manufacturing Setup

The testing of additive manufacturing with clay took place with a Delta WASP 2040 at TU Delft's LAMA lab. The printer operates using a g-code to control nozzle movement, acceleration, and extrusion rate along the toolpath. Printing performance depends on the interaction between paste rheology, geometric complexity, and printing parameters. The viability of printing a form is equally dependant on desired form, the quality of this translation, and the material consistency. Printing parameters such as nozzle diameter, extrusion rate, and layer height were iteratively adjusted during printing trials to achieve stable extrusion and consistent layer deposition.

2.3 Drying and Firing Protocol

After printing, the samples were subjected to a controlled drying and firing protocol to stabilize the ceramic material prior to mechanical and physical testing. The dried specimens were fired in a ceramic kiln using a staged firing schedule. The heating schedule gradually removed residual moisture and organic binder components before reaching the sintering temperature required for ceramic consolidation. Controlled heating rates were applied to minimize thermal stresses, and after firing, the samples were cooled gradually inside the kiln to reduce thermal shock.

Dimensional measurements were recorded before and after firing to quantify linear shrinkage as the percentage reduction relative to the printed geometry.

2.4 Mechanical and Physical Testing

Mechanical and physical properties of the ceramic composites were evaluated through laboratory testing of both green (unfired) and fired samples.

Compression tests were conducted to assess the structural integrity of the printed specimens. Green compression tests evaluated the load-bearing capacity of the material prior to firing. Fired compression tests determined the final mechanical strength of the ceramic composite.

Porosity and water absorption were determined through mass and volume measurements before and after water immersion. Shrinkage was calculated by comparing specimen dimensions before and after firing. Tests followed standard ceramic characterization procedures with reference to relevant ISO and EN testing standards where applicable [10]. The material characterization results were used to evaluate the suitability of the recycled ceramic composite for the fabrication of acoustically tuned Helmholtz resonator modules.

2.5 Digital Acoustic Design Workflow

Equation (1) was used to design a resonator aiming for a certain target frequency.

$$f = \frac{c}{2\pi}\sqrt{\frac{S}{lV_0}} \tag{1}$$

f is the resonant frequency, c is the speed of sound, S is the cross-sectional area of the neck, V_0 is the volume of the cavity, and l is the effective length of the neck. For the most accurate results, the neck's effective length l includes an "end correction" (Δl) which accounts for the air mass vibrating at the opening.

Each resonator was tuned to a specific target frequency at which sound absorption was maximized. By combining multiple resonators within a single tile, a broader frequency range was addressed, further expanded by arraying the tiles on a larger surface. This enabled the design of acoustic panels targeting low-frequency traffic noise. Tile optimization was achieved through Visual Programming Software Grasshopper, and the evolutionary optimizer Galapagos. Among the different combinations of quantity, location and neck dimensions, Galapagos identified optimal resonator arrangement, considering the limits of 3D printing. Optimized resonator was printed to ensure correct fabrication method. Furthermore, acoustic testing with an impedance tube, a laboratory device used to measure the acoustic properties of the material, validated results of digital acoustic design.

3 Results

3.1 Printability and Extrusion Stability

Stable extrusion was achieved for formulations up to approximately 40% recycled ceramic content (B40), enabling consistent layer deposition and geometric control (see Fig. 1). However, increased geometric complexity introduced challenges in toolpath continuity, resulting in defects such as cracking, void formation, and inconsistent layer adhesion. These issues indicate that both material composition and geometry significantly influence printability and fabrication reliability.



Fig. 1. Samples printed using different mixtures and printer parameters

3.2 Shrinkage and Porosity Trends

A clear relationship was observed between recycled content, shrinkage, and porosity. All formulations exhibited low firing shrinkage (≤4%), with ceramic particles acting as stabilizing aggregates. However, increasing recycled content led to higher porosity (approximately 10–20%) due to reduced clay content and limited densification during firing. This introduces a trade-off, where higher waste content improves circularity but reduces structural cohesion and mechanical performance.

3.3 Mechanical Performance

Compression testing revealed distinct differences between green and fired states. Increasing recycled content reduced green strength due to limited plastic bonding, leading to deformation above 40% waste content. After firing, the optimized B40 formulation achieved compressive strengths of approximately 18–22 MPa, comparable to the virgin clay reference. Higher waste fractions (>50%) resulted in a sharp reduction in strength, confirming a critical threshold around 40% recycled content. These findings extend existing studies, which typically limit recycled ceramic content to 30–35% for extrusion-based additive manufacturing [4, 8].

3.4 Acoustic Performance (Preliminary Validation)

Impedance tube tests proved the concept of Helmholtz resonator combined with 3D printing of a singular PLA module to be successful, demonstrating sound absorption of 0.75 (where 0 = full reflection, and 1 = full absorption) at a frequency of 320 Hz. This corresponds to the theoretical calculations for the specific volume (see Fig. 2).

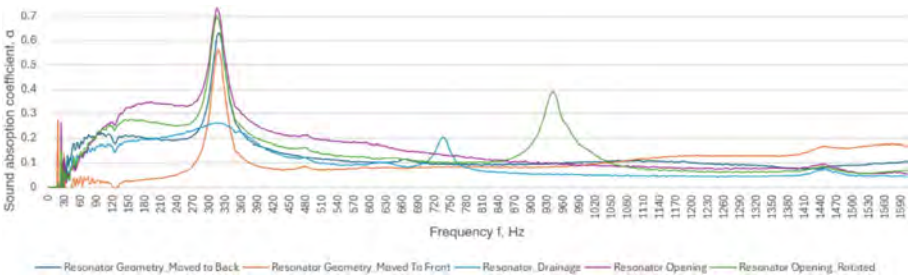


Fig. 2. Impedance Tube Results, Acoustic Testing

3.5 Preliminary Environmental Hotspot Analysis

Manufacturing (A3), particularly kiln firing, was identified as the dominant contributor to global warming potential (GWP), accounting for up to 76% of total emissions. Process optimization, including reduced firing duration and localized material sourcing,

lowered GWP to 0.353 kg CO_2 eq/kg (~21 kg CO_2 eq/m^2), representing a 63% reduction (Table 1). Despite these improvements, emissions remain higher than conventional ceramic tiles, indicating the need for further optimization of firing processes.

Table 1. Key reductions in CO_2 as per the optimized results.

Scenario	GWP (kg CO_2 eq/kg)	GWP (kg CO_2 eq/m^2)	Key Reductions
Baseline	0.963	~45	–
Optimized	0.353	~21	63% total (firing −57%, transport −84%)

4 Discussion



Fig. 3. Development of Helmholtz resonator modules: PLA prototypes, ceramic printing trials, and final geometries used for acoustic validation.

This study demonstrates that recycled ceramic content can be increased to ~40% in extrusion-based additive manufacturing, exceeding current reported limits while maintaining structural and fabrication performance. However, when the recycled fraction exceeds a critical threshold, the mixture contains insufficient clay to maintain stable extrusion and layer adhesion. This results in nozzle clogging, irregular extrusion, and reduced green strength (see Fig. 3 for results). Extrusion-based additive manufacturing enables the production of complex geometries with minimal material waste. This capability is particularly valuable for acoustic components such as Helmholtz resonators, which require precise geometric tuning [6, 9, 14].

Previous studies investigating recycled ceramics in additive manufacturing typically report recycled fractions between 30% and 35% to maintain printable rheology and mechanical stability. The results of this study demonstrate that the recycled content can be increased to approximately 40% while maintaining functional performance, expanding the potential for circular material strategies in ceramic additive manufacturing [4, 8].

The findings also highlight broader implications for circular construction systems. Ceramic waste generated through demolition or manufacturing can be reintroduced into new architectural products through localized material loops [5, 7]. When combined with

additive manufacturing, recycled materials can be transformed into customized building components such as acoustic façade panels or modular noise barriers. This approach supports urban mining by converting locally available waste streams into functional architectural elements and adaptable acoustic envelopes.

Despite the promising results, several limitations remain. First, the experiments were conducted at prototype scale, and further research is required to evaluate the scalability of the material system for industrial production. Second, acoustic testing was limited to a small number of prototypes, and additional experiments are needed to better understand the relationship between material porosity, surface roughness, and acoustic performance. A full life cycle assessment and improved printing reliability should be addressed in future work.

5 Conclusion

This research demonstrates the feasibility of integrating recycled ceramic waste into extrusion-based additive manufacturing for acoustically functional components. Up to 40% recycled content was achieved while maintaining printability and mechanical performance, representing a balance between circularity and fabrication stability.

Helmholtz resonator geometries were successfully fabricated, achieving a peak absorption coefficient of 0.75 at 320 Hz. Preliminary analysis indicates potential carbon reductions of up to 63%, although kiln firing remains the dominant impact.

Overall, the findings highlight the potential of combining recycled materials, parametric acoustic design, and digital fabrication to develop circular architectural systems for urban noise mitigation.

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Insights into the Fracture Mechanics of Fibre-Reinforced Asphalt Mixtures

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Abstract. Not all commonly used engineering materials are fully understood, a challenge that is particularly pronounced in heterogeneous and viscoelastic composites such as asphalt mixtures. Various additives are widely used to enhance the performance of asphalt mixtures, among which fibres show significant potential for reinforcement and crack mitigation. This paper aims to provide deeper insight into the fracture mechanics of selected fibre-reinforced asphalt mixtures. Load–displacement diagrams obtained from the semi-circular bending (SCB) test are analysed to demonstrate the reinforcing potential of fibres and to better elucidate the mechanisms and onset of crack formation in asphalt mixtures. Additionally, new perspectives for a more precise evaluation of fracture behaviour in asphalt mixtures are presented.

Keywords: Reinforcement · Fibres · Crack · Fracture mechanics · SCB test

1 Introduction

Aspalt mixtures are the most widely used material for paved roads. They represent a heterogeneous viscoelastic composite consisting of asphalt binder, aggregate and mineral filler. Air voids are naturally created during compaction and various additives can be incorporated to enhance selected mechanical properties. The asphalt binder governs the viscoelastic behaviour, rheological properties and temperature susceptibility of the mixture, while the aggregate skeleton plays a dominant role in stress transfer at higher temperatures. Due to the irregular shape and random spatial distribution of aggregate particles, significant variability in mechanical properties can occur during laboratory testing, which complicates the description of the material behaviour.

Cracking is one of the most critical deterioration mechanisms in asphalt pavements. Crack initiation and propagation significantly reduce pavement service life by decreasing ride comfort and safety and by allowing water to penetrate into the pavement structure, which accelerates further deterioration. Therefore, understanding the mechanisms governing crack initiation and propagation is essential for improving pavement durability.

In recent years, fibre reinforcement has attracted increasing attention as a method for enhancing the cracking resistance of asphalt mixtures. Fibres may improve stress

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redistribution, delay crack initiation and act as crack-bridging elements during crack propagation. The semi-circular bending (SCB) test has become a widely used laboratory method for evaluating the fracture behaviour of asphalt mixtures because it allows the characterization of both crack initiation and propagation through analysis of the load–displacement response [1, 2].

The objective of this study is to investigate the fracture behaviour of selected fibre-reinforced asphalt mixtures using SCB testing and to analyse how fibre reinforcement influences crack initiation and crack propagation mechanisms.

1.1 Resistance to Crack Propagation of Asphalt Mixtures in SCB Test

A widely used laboratory method for evaluating resistance to crack propagation is the semi-circular bending (SCB) test. A modified version of the test used at the Faculty of Civil Engineering, CTU in Prague is explained in [3]. The main European document for the evaluation of fracture behaviour of asphalt mixtures is EN 12697–44. The standard is primarily based on linear elastic fracture mechanics and focuses mainly on parameters related to crack initiation, while the post-peak propagation behaviour after the maximum load (point P in Fig. 1) is not explicitly addressed. However, due to the viscoelastic and heterogeneous nature of asphalt mixtures, the post-peak behaviour often provides important information about crack propagation mechanisms. Therefore, alternative evaluation approaches are frequently used in scientific research.

Fracture work is defined as the mechanical work required to initiate and propagate a crack and corresponds to the area under the load–displacement curve:

$$W = \int_0^{\Delta f} F(\Delta) d\Delta \tag{1}$$

where $F(\Delta)$ is the applied load and Δ_f is the displacement corresponding to the termination load level. For interpretation of crack initiation and crack propagation, the fracture work can be divided into two parts:

$$W_{pre} = \int_0^{\Delta p} F(\Delta) d\Delta \tag{2}$$

$$W_{crack} = \int_{\Delta p}^{\Delta f} F(\Delta) d\Delta \tag{3}$$

where Δ_p is the displacement corresponding to the peak load.

$$W_{tot} = W_{pre} + W_{crack} \tag{4}$$

Fracture energy is obtained by normalizing fracture work with respect to the ligament area above the notch:

$$G_f = \frac{W_{tot}}{b * (H - a)} \tag{5}$$

where b is specimen thickness, H is specimen height and a is notch depth.

Idea of using fracture work and fracture energy is clear – the more energy is spent on a crack initiation and its propagation, the stronger the SCB specimen and asphalt mixture consequently is. Since the behaviour of viscoelastic composites is complex, other indexes were implemented for more effective evaluation. Among others, flexibility index (FI) is strongly established [4]. It gives information about crack propagation speed and helps to evaluate, whether mixture's post-peak response is brittle or ductile.

$$FI = A^{*}Gf/|m| \tag{6}$$

where G_f is fracture energy, defined as the area under the load-displacement curve (work of fracture) divided by the product of the ligament length and specimen thickness, J/m^2; m represents the post-peak slope in the inflextion point of load-displacement curve, kN/mm; and A is a calibration coefficient (0.01) [4].

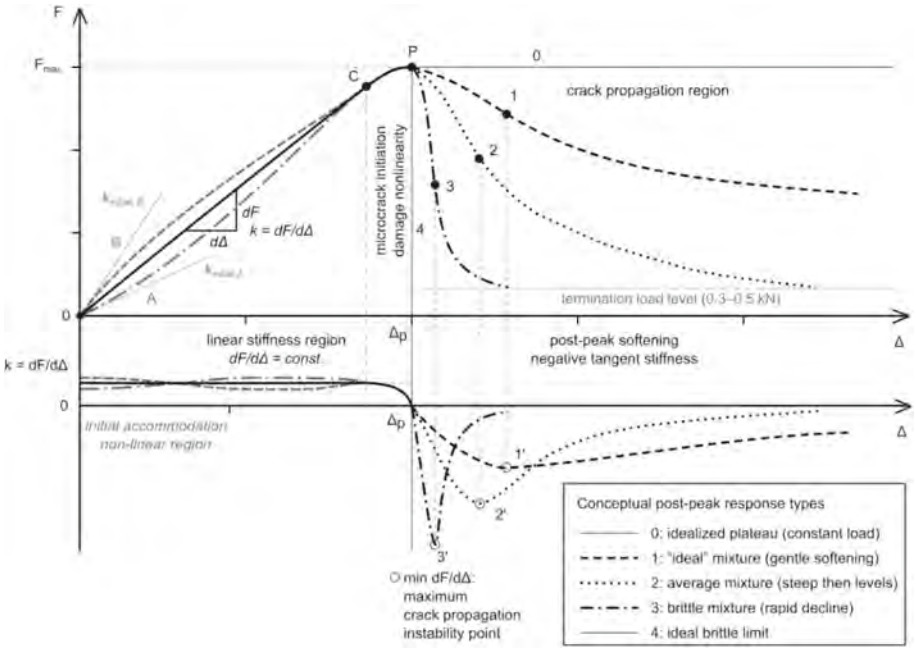


Fig. 1. A schematic picture of typical SCB force-displacement diagram at 0 °C with stiffness-displacement on the lower axis. The region of microcrack initiation (between points C and P) is not always present. In the specimens of stiffer asphalt mixtures, a crack tends to initiate and propagate rapidly (brittle cracking).

Figure 1 illustrates a typical load–displacement (L–D) response of a bitumen mixture tested at 0 °C. Two main regions can be distinguished: the pre-peak region and the post-peak (crack propagation) region, separated by the peak load (point P). In theory, the response should remain linear up to the maximum load according to linear elastic fracture mechanics. In practice, however, asphalt mixtures often exhibit deviations from ideal linear behaviour due to material heterogeneity and early microcrack formation.

After an initial accommodation region, the curve typically remains approximately linear until point C, where microcrack initiation begins. This stage is followed by progressive softening as the peak load is approached. At the peak load, the tangent stiffness of the curve becomes zero. Once crack propagation begins, the load decreases and the curve usually reaches an inflection point corresponding to the minimum tangent stiffness and maximum crack propagation instability. The inflection point of the load–displacement curve corresponds to the minimum value of the tangent stiffness $dF/d\Delta$, which represents the stage of maximum crack propagation instability in the specimen.

Residual resistance is recorded until a termination load level is reached. In practice, the termination load is at FCE CTU in Prague experiments typically set to approximately 0.3 kN for mixtures with nominal maximum aggregate size (NMAS) smaller than 16 mm and 0.5 kN for mixtures with NMAS greater than 16 mm.

1.2 Fibres in Asphalt Mixture from a Mechanical Point of View

Various types of fibres have been incorporated into asphalt mixtures to improve their mechanical performance. From a mechanical perspective, fibres with higher stiffness than the surrounding matrix can contribute to stress transfer and redistribution within the composite. The reinforcing efficiency of fibres depends on their material properties, geometry (length, diameter and aspect ratio) and surface characteristics.

Surface properties play a crucial role because effective stress transfer between the matrix and the fibre requires sufficient interfacial bonding. These properties include both physical characteristics (surface roughness and surface area) and chemical compatibility with the bitumen matrix.

From the viewpoint of fracture mechanics, fibres may improve cracking resistance by redistributing tensile stresses during microcrack formation, delaying crack propagation and acting as crack-bridging elements after crack initiation. Provided that the anchoring length is sufficient, fibre bridging may increase the ductility of the mixture and consequently increase the post-peak fracture work W_{crack} and total fracture work of test W_{tot} consequently.

2 Materials

For the investigation of fracture mechanics of asphalt mixture with fibres, 4 mixtures of asphalt concrete for binder layers AC_{bin} 16+ with NMAS = 16 mm were produced with the same aggregate size distribution curve (according to the Czech technical standard CSN 73 6121:2019 denoted as ACL 16+). For control mixture and 2 mixtures with fibres, a standard binder 50/70 was used. A polymer modified bitumen (PMB) 25/55–65 was used for the second mixture without fibres. Mixing and compaction temperatures were 150 °C for the binder 50/70 and 160 °C for the PMB.

Furthermore, 20 mm long jute fibres were used in this study as a 3D reinforcement. The fibre content was 0.2% by weight. The irregular, fragmented surface of natural plant-based fibres should provide high interphase mechanical adhesion. In one mixture, the fibres were treated with mild 0.5% NaOH solution for 24 h. After the drying, a hydrophobic layer was sprayed onto the fibres and fibres were left to dry again. In the

process, a complex resin/nano particle network was formed on the surface, making the fibres hydrophobic and thus, more chemically compatible with the bitumen matrix. The hydrophobization solution was provided by a Slovak company Nanosystem, s.r.o. The asphalt mixes were produced and tested in the lab according to the Czech national specifications given in the national standard ČSN 736121:2019. Mixtures were compacted according to EN 12697–30 (by Marshall impact compactor) with 2x50 blows and their preview is shown in the Table 1.

Table 1. AC_{bin} 16+ (ACL 16+) mixtures produced and tested

Mixture's label	Binder	Description
REF.	50/70	Control mixture without additives
J2	50/70	0.2% by weight 20 mm raw jute fibres
J2_T	50/70	0.2% by weight 20 mm treated jute fibres
PMB	PMB 25/55–60	Second control mixture with modified bitumen

To evaluate the performance of asphalt mixtures, a selection of laboratory tests was performed and examined: (i) air voids according to EN 12697–8; (ii) determination of stiffness according to EN 12697–26, Annex C: IT-CY test method; (iii)resistance to crack propagation according to ČSN EN 12697–44 with a modified procedure: loading rate (2.5 mm/min), length of test specimens 100 mm (IT-CY based) [3].

3 Results and Discussion

3.1 Air Voids

The air voids data are summarized in Table 2. Control mixture and mixture J2_T met the type testing (mix design) criterion for air voids (4.0–6.0%; ČSN 73 6121:2019). All the tested mixtures met the control criterion range between 3.0–8.0% for AC_{bin} 16+ (ČSN 73 6121:2019). Mixture with PMB exhibited the highest air void content of 6.7%. Hydrophobic treatment of jute fibres has led to an increase in bulk density and decrease of air voids.

Table 2. Air voids of AC_{bin} 16+ mixtures

Mix	Bulk density [g.cm^{-3}]	Maximum density [g.cm^{-3}]	Air voids [%]
REF.	2.412	2.521	4.3
J2	2.358	2.523	6.5
J2_T	2.404	2.557	6.0
PMB	2.360	2.530	6.7

3.2 Stiffness (IT-CY)

The stiffness modulus test was conducted on Marshall specimens at four temperatures 0 °C, 15 °C, 27 °C and 40 °C. The results are shown in Table 3. Control mixture (REF.) and mixture J2_T with treated fibres recorded the highest stiffness at 0 °C. We could claim that these two mixtures are prone to thermal induced cracking. Observing parameter of thermal susceptibility (TS), which was calculated as a ratio between stiffness at 0 °C and stiffness at selected temperature, can give us a clearer picture. Mixtures with lower TS values have more balanced thermal response regarding their stiffness. Control mixture with 50/70 binder had the highest value of TS, thus the highest risk of thermal induced cracking with possible brittle behaviour at low temperatures.

Table 3. Stiffness modulus (S_m [MPa]) of AC_{bin} 16+ mixtures. Thermal susceptibility (TS) is on the right side. Standard deviation σ written in Italic is next to the stiffness values.

	0 °C		15 °C		27 °C		40 °C		TS	
Mix	S_m	σ	S_m	σ	S_m	σ	S_m	σ	*S0/S27*	*S0/S40*
REF.	21 546	*543.6*	10 160	*419.1*	3 687	*207.2*	1 234	*64.6*	5.8	17.5
J2	18 746	*553.9*	10 361	*384.2*	4 394	*238.3*	1 528	*93.2*	4.3	12.3
J2_T	21 857	*673.4*	12 022	*345.9*	4 487	*316.6*	1 860	*177.7*	4.9	11.8
PMB	19 862	*230.0*	11 802	*318.7*	4 356	*430.9*	1 453	*116.8*	4.6	13.7

Another source of stiffness data lies in SCB test. From Fig. 2., we can use the L-D curve of SCB test to visually identify (*k_graph*) and numerically calculate (*k_num*) the tangent stiffness. Both methods were used and the results are presented in Table 4. We can notice that results from different test methods does not match. The direction of the load on specimen regarding the compaction direction is the same for SCB test as for IT-CY. However, each test has different geometry of specimen and configuration. Furthermore, a monotonic load applies during SCB test and IT-CY method uses pulses. Therefore, we can observe a decrease of *k_num* and *k_graph* in comparison to IT-CY.

Table 4. Stiffness of AC_{bin} 16+ mixtures at 0 °C from linear stiffness region of SCB test.

	k_graph			*k_num*		IT-CY	
Mix	[MPa]	σ	R^2	[MPa]	σ	[MPa]	σ
REF.	13 180	*902*	*0.9943*	16 800	*400*	21 546	*543.6*
J2	14 762	*3 931*	*0.9887*	16 600	*3 262*	18 746	*553.9*
J2_T	15 092	*3 132*	*0.9902*	18 417	*3 347*	21 857	*673.4*
PMB	13 533	*1 990*	*0.9934*	15 667	*2 285*	19 862	*230.0*

3.3 Resistance to Crack Propagation (SCB Test)

The compacted Marshall specimen was cut into two semi-circular specimens. The specimen's diameter was reduced from 150 ± 1 mm as defined in the standard (EN 12697–44) to 101 ± 1 mm. The loading rate was reduced from 5.0 mm/min as set in the standard to 2.5 mm/min (EN 12697–44), which leads to a more accurate load-displacement curve. The results are presented for the 0 °C.

Table 5. Selected parameters of SCB test. $K_{I,c}$ is the critical value of resistance to crack propagation (fracture toughness) at 0 °C. Complete dataset for 25 °C is not presented in this paper.

	$K_{I,c}$ 0 °C		W_{pre} 0 °C		W_{crack} 0 °C		W_{tot} 0 °C		FI 0 °C		W_{pre} 0 °C/ W_{pre} 25 °C	W_{tot} 0 °C/ W_{tot} 25 °C
Mix	[N/mm$^{3/2}$]	σ	[J]	σ	[J]	σ	[J]	σ	[−]	σ		
REF.	36.2	*3.2*	1.8	*0.4*	0.5	*0.5*	2.3	*0.5*	11.0	5.0	1.80	1.02
J2	37.0	*4.5*	2.4	*0.9*	1.9	*0.9*	4.3	*0.9*	40.0	18.0	2.18	1.39
J2_T	40.7	*2.8*	2.3	*0.4*	0.5	*0.5*	2.8	*0.5*	27.0	–	1.64	0.85
PMB	36.7	*2.3*	2.1	*0.5*	0.6	*0.5*	2.7	*0.5*	18.0	8.0	1.24	0.64

Observing Table 5, three mixtures have similar fracture toughness between 36.2 and 37.0 N/mm$^{3/2}$. Interestingly, chemical treatment of fibres has led to an increase in $K_{I,c}$ to 40.7 N/mm$^{3/2}$. Both mixtures with jute fibres achieved the highest pre-peak fracture work W_{pre}. However, mix J2 exhibited by far the highest fracture work in the crack propagation region W_{crack} and the highest flexibility index (FI). This behaviour may be attributed to weaker interfacial adhesion between untreated fibres and the bitumen matrix. After crack initiation, fibres may gradually pull out from the matrix rather than break, which increases the energy required for crack propagation. Nevertheless, the J2 mixture also exhibited a relatively large standard deviation, indicating considerable scatter between individual specimens.

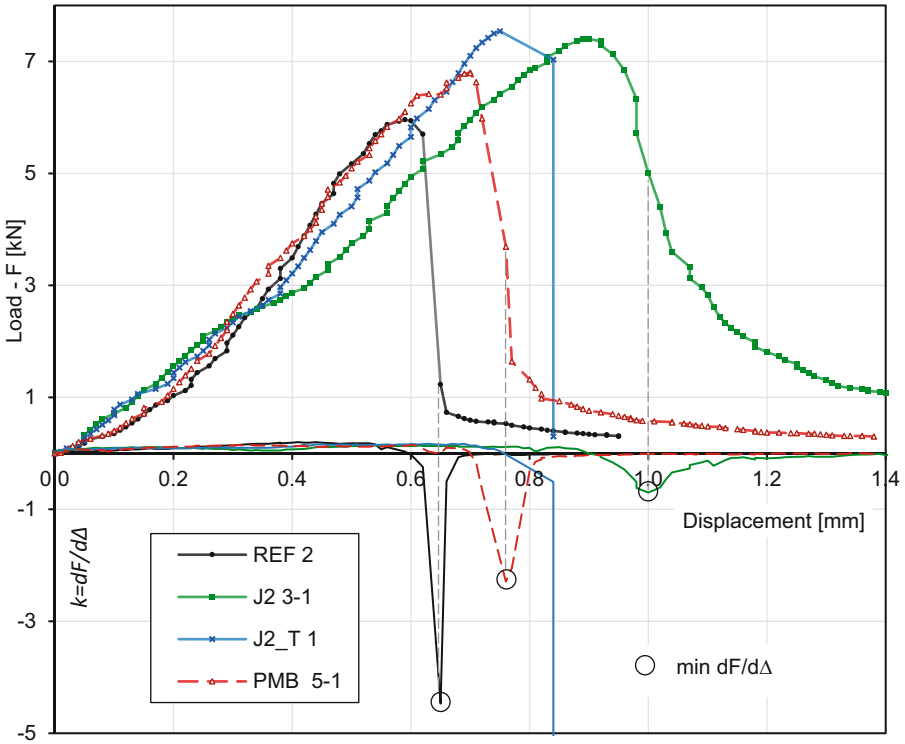


Fig. 2. Selected typical L-D curves of tested AC_{bin} 16+ mixtures at 0 °C.

Typical L-D curves of SCB test at 0 °C from each mixture can be seen in Fig. 2. For the J2_T mix, a brittle specimen was selected. Even though, the W_{crack} is still higher, than in the case of control mix. Moreover, the tangent stiffness k is drawn around the horizontal axis and below it. It can be concluded that the higher min $k = dF/d\Delta$ is, the higher the ductility and FI.

4 Conclusion

Four AC_{bin} 16+ mixtures were investigated to evaluate the influence of fibres and binder modification on fracture behaviour.

The results indicate that the incorporation of jute fibres increases the *air voids* of asphalt mixtures. However, hydrophobic treatment of fibres improved their chemical compatibility with the bitumen matrix, resulting in higher bulk density and lower air void content. *Stiffness modulus* results showed that mixtures containing PMB and fibre reinforcement exhibit a more balanced thermal response compared with the reference mixture. The control mixture with conventional paving grade bitumen 50/70 showed the highest thermal susceptibility and therefore the highest potential risk of brittle behaviour at low temperatures. Stiffness values obtained from the SCB test were lower than those measured using the IT-CY method, which can be explained by differences in loading

configuration, specimen geometry and loading mode. Analysis of *SCB* load–displacement curves indicates that fibre reinforcement mainly influences the post-peak behaviour of the mixtures. Untreated jute fibres significantly increased the fracture work associated with crack propagation, suggesting that fibre pull-out mechanisms contribute to higher energy dissipation during crack growth. In contrast, the PMB mixture showed the most balanced fracture response between low and moderate temperatures.

Overall, the results suggest that fibres primarily influence crack propagation mechanisms, while polymer-modified binders improve the overall balance of mechanical response. Further research should focus on a more detailed investigation of fibre–matrix interaction and its influence on fracture processes in asphalt mixtures.

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Shear Strength Performance of a Biobased and Biodegradable Mortar Based on Lupin Protein

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Abstract. A growing market for sustainable building materials requires the development of ecofriendly adhesives and mortars, to match the characteristics of the building products themselves. This article presents the development of a biobased, biodegradable, non-mineral mortar made from regionally sourced European ingredients, all of which prepared for climate change. Lupin protein acts as the binder. Adding lime water activates the binder, turning the mixture into an adhesive. The addition of further bulking agents, such as lupin fibres for the smallest fraction and sawdust for the larger fractions, increases the volume, using low-cost materials. Different parameters in the production of the mortar have been constantly tested as ingredient ratios, other bulking agents and manufacturing methods, all aiming for high adhesive and shear strength. The focus of this article is on the raw materials used in the basic mixture, the manufacturing methods and the development of shear strength in relation to the drying process of the mortar. Its biodegradable nature supports the principles of a circular economy and can reduce dependence on common mineral and synthetic binders. Examples of applications may include masonry with novel materials such as StrawBricks and Sugarcrete, sealing prefabricated wooden elements and bonding wood fibre insulation boards to facades. This biobased, biodegradable mortar supports the adoption and development of more sustainable, climate-adapted, circular construction practices.

Keywords: Biobased Mortar · Biodegradable Mortar · Lupin Protein · Sustainable Building Material · Circular Building Material

1 Introduction

Striving for a circular economy and addressing the global climate crisis, there are significant opportunities to reduce the environmental footprint of the building and construction sector by using agricultural and forestry products and by-products. Currently, the sector is responsible for around one-third of global waste, most of which is sent to landfill or incinerated, plus approximately 34% of global CO_2 emissions [1]. This makes decarbonisation and circularity key targets for policymakers and NGOs around the world.

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1.1 A Growing Market

With new biobased materials constantly entering the market, there is a need to adopt technologies and construction methods to contribute to a stronger circular economy and enable the full potential of these new products.

Masonry is a widespread construction method for centuries, still accounting for approximately 70% of all new housing built in Germany in 2020 [2], offering a vast market where new biobased materials could step in. Reducing the use of common, mineral and environmentally harmful building products immediately reduces CO_2 emissions and, in a long run, reduces building and construction waste in landfills and incineration. Keep using masonry construction allows builders to change the materials while continuing with the same processes, simply transferring their know-how.

With masonry blocks like StrawBrick [3], Sugarcrete [4], as well as hemp blocks, on the edge of a growing market, alternatives capable of achieving holistic circularity will soon be available. To realise the full circular potential of these materials, a suitable mortar or adhesive is needed that provides low thermal conductivity for potentially monolithic constructions that come with those materials and is biodegradable in an end-of-life scenario.

1.2 Concept for the Biobased and Biodegradable Mortar

The key ingredient in the mortar is lupin protein isolate (see sect. 2.1), which acts as a binder. The decision to use a formulation based on protein glue is due to the necessity for high adhesiveness and shear strength at an early stage of the mortar application. Furthermore, the decision is made to use lupin proteins derived from a native European, climate resistant species that can even be grown as a catch crop [5], without putting additional pressure on food farming.

The mortar formulation uses water as a solvent, meaning it is water-based and there is no risk of toxic emissions. An alkaline environment, created by calcium oxide, activates the adhesive properties of the lupin protein. This activation is necessary as the proteins are amphiphilic [6], a characteristic describing their partly hydrophobic and hydrophilic properties. Once activated, the water forms stronger bonds, resulting in improved processing capabilities and stronger adhesion. Unlike concrete, which gains strength through a chemical hydration process, the biobased mortar based on lupin proteins develops immediate adhesion and achieves its full strength exclusively through physical drying through water evaporation.

Further, low-cost bulking agents are added to the formulation, reducing the amount of binder required for use as a mortar where joints of several millimetres are needed to compensate for variations in masonry materials. In line with the circular economy, by-products from other industrial processes are used as bulking agents. Sawdust from a local sawmill processing softwood, and lupin fibres as a residue from lupin protein extraction, are used as different fractions.

Detailed information on the raw material conditions is provided in Sect. 2.1, while Sect. 2.2 explains the manufacturing process, including the formulation for the biobased and biodegradable, non-mineral mortar.

2 Methods

This research focuses on comparing the shear strength of the mortar with its drying behaviour. The study is based on testing sets of four samples, all of which are manufactured on the same day and treated the exact same way.

2.1 Processing and Conditioning of the Raw Materials

In preparation for mixing the mortar, it is necessary to properly process and condition all the raw materials and ingredients. The prepared and conditioned ingredients are shown in Fig. 1.

Lupin Protein. The lupin protein isolate used is a beige to light brown, dry powder derived from blue lupins grown and harvested in northern Germany, primarily for food applications. Once harvested, the lupin seeds are ground and de-oiled in an acidic environment. Next, the protein is extracted in a slightly alkaline environment before being dried [7]. According to the producer, the resulting material is highly pure, with a protein content of 90% and a dry matter of around 95% [8].

Lupin Fibre. A residue of the lupin protein extraction are lupin fibres. These fibres are rather fine due to the grinding of the lupin seeds and are dried to a dry matter content of about 95% for our application. The material has a high cellulose content of about 63–73% [9] and a fine, crisp texture ranging from 0.5–2.0 mm.

Calcium Oxide. For the mortar, ordinary quicklime (CaO) is used without any further conditioning.

Sawdust. This material is sourced from a local sawmill, where it is a by-product of lumber processing. Only softwood has been processed at this facility before the material was collected. To generate an interlocking mixture, the sawdust is sieved into different fractions using sieves similar to those used in concrete production. The fractions used are 1–2 mm and 2–4 mm. After sieving, the sawdust is conditioned at a standard climate of 20 °C (+3 °C / −2 °C) and (60 ± 5) % relative humidity (rH) for a minimum of one week and until the mortar is mixed.

Water. Tap or spring water can be used equally well if it is of good quality and does not smell of chlorine. The water temperature is 20 °C ± 2.

2.2 Manufacturing Process of the Mortar and Sample Preparation

The mixing of the mortar starts with adding the quicklime to the water and leaving it to react for two minutes. Next, all the other ingredients are added at once and the mixture is continuously stirred for five minutes using a mixer at low speed. The exact standard formulation used for all samples is shown in Table 1.

Once mixing is complete, the mortar should be left to rest to allow the soft foam that forms during mixing to settle. After resting for about 10 min, the mixture is mixed again for two minutes, destroying large parts of the foam bubbles. The mortar is now ready for application.



Fig. 1. Prepared materials for the mortar mixture, from left to right: lupin protein isolate, lupin fibre, calcium oxide, sawdust 2–4 mm and sawdust 1–2 mm (Pracht, 2026).

Table 1. Standard formulation for the biobased and biodegradable mortar (Pracht, 2026).

Material	Weight [g]	Share by Weight [%]
lupin protein	100	11.6
lupin fibre	75	8.7
calcium oxide (CaO)	15	1.7
sawdust 1–2 mm	30	3.5
sawdust 2–4 mm	45	5.2
water	600	69.4

Sample preparation follows DIN EN 1052–3 using 'type I' samples, with adaptations to the materials and their size. As the research focusses on applications involving biobased construction materials, three-layer cross laminated timber (CLT) is selected as the base material instead of the mineral materials commonly specified in the standard. Each sample comprises three 19 mm pieces of CLT, with two 7 mm mortar joints. The two outer CLTs measure 100 x 100 mm, while the middle piece measures 100 x 120 mm, leaving one end exposed to facilitate later testing, as illustrated in Fig. 2. With two 7 mm heigh and 5 mm deep spacers to ensure the correct joint thickness, the remaining mortared surface measures 100 x 90 mm or 9000 mm^2. When applying the mortar, a small protrusion is created to ensure thorough contact of both surfaces according to the standard. This procedure is completed for both mortar joints of a sample before the spacers are removed. When finished, all samples are stored in a standard climate chamber until the day of testing.

2.3 Testing Procedures

Drying and Observation of the Process. All samples are stored in standard climate conditions of 20 °C (+3 °C / −2 °C) and (60 ± 5) % relative humidity (rH) according to DIN EN 1015–11 until the day of testing.

To observe the drying of the mortar, the weight of each sample is documented (accuracy: 0.1 g) once every weekday from day 0 for four weeks. From week five onwards, the weight is taken every second weekday, and then weekly from week six

onwards. To determine the weight of the mortar alone, the weight of all three CLTs that comprise each sample is recorded and subtracted from the observed weight.

For determining the degree of dryness, as shown in Fig. 3, the remaining water content of the mortar is calculated as a percentage of the amount of water originally added in the standard mortar formulation (see Table 1).

Initial Shear Strength Testing. The testing of the initial shear strength is carried out according to DIN EN 1052–3, 'Methods of Test for Masonry', using 'type I' and 'procedure B'. A qualified testing machine is used; the setup is shown in Fig. 2.

Within the framework of the standard, a precompression of 0.1 kN is applied to ensure firm contact between the sample and the machine prior to testing. Furthermore, the shear stress rate is increased with 52.5 N/s, which, at 0.175 N/(mm^2/min), lies within the standard's specified range of 0.1–0.4 N/(mm^2/min). Testing ends at a physical compression of 11 mm.

Each testing involves a set of four samples to generate averages. According to 'procedure B' the maximum measured values of the shear strength are converted into N/mm^2, and the mean initial shear strength, f_{vo} [N/mm^2], is calculated. The characteristic initial shear strength, f_{vok} [N/mm^2], is calculated with the simple method using Eq. (1), in order to be comparable with the requirements of the applicable standard DIN EN 998–2, 'Specification for Mortar for Masonry'.

$$f_{vok} = 0.8 \bullet f_{vo} \tag{1}$$

A deviation from the standard is a lateral guidance added at the foot of the samples without load. This ensures correct positioning of all samples and prevents any undesirable movement. To determine the shear strength unaffected by this deviation, one set is tested without lateral guidance and serves as a reference for standard testing.

To evaluate how shear strength develops in relation to the drying process, the initial shear strength is tested when the samples are 1, 2, 4, and 8 weeks old.

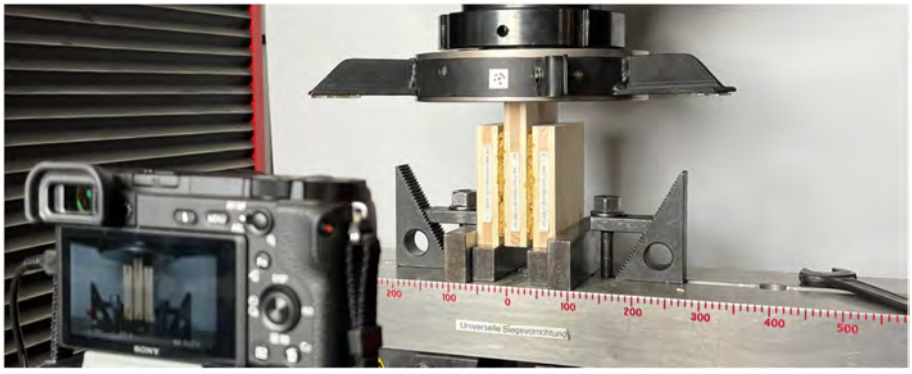


Fig. 2. Setup for initial shear strength testing according to DIN EN 1052–3 with a sample and added lateral guidance (Pracht, 2026).

3 Results and Discussion

3.1 Drying

As water acts as the solvent in the formulation of the biobased and biodegradable mortar, its strength depends heavily on the drying process. Fig. 3 shows the drying process as a graph, indicating the amount of remaining water within the mortar compared to the amount originally added as a solvent. The graph falls more steeply during the first weeks after the samples are manufactured, showing the mortar's drying progress, and slowly turns into a logarithmic shape. This is a common behaviour for a material approaching its equilibrium moisture content whilst drying in a climate-controlled environment.

A noticeable finding is that, from approximately four to five weeks past manufacturing, an extreme delay in drying occurs at a level of approximately 10–15% of water remaining in the mortar. This finding can be explained by several theories, which are likely to be interacting.

Firstly, it should be noted that the equilibrium moisture content is not reached by the end of the graph and when the last testing took place, as the drying process was not expected to exceed eight weeks. The early slowdown of the drying is likely to be due to the increasing impermeability of the outer shell of the mortar.

Secondly, some of the water remains chemically bonded to the other ingredients in the mortar. For example, when calcium oxide (CaO) hydrates to form calcium hydroxide ($Ca(OH)_2$), it binds the water, permanently increasing the molecular weight and thus the weight of the mortar.

Thirdly, both the lupin protein isolate and the lupin fibre were not conditioned to the standard climate prior to manufacturing the mortar, as the relatively high humidities are harmful to their key properties. Therefore, some of the remaining water in the mortar is necessary to increase the moisture of these ingredients and reach the equilibrium moisture content for the entire formulation.

3.2 Initial Shear Strength

The diagram in Fig. 3 shows the initial shear strength in relation to the drying progress of the mortar over a period of eight weeks. The initial shear strength has been tested 1, 2, 4, and 8 weeks after the samples were manufactured. At one week, the characteristic initial shear strength (f_{vok}) is relatively low at 0.08 N/mm^2 with 74% of the water still remaining in the mortar. Two weeks past manufacturing, the f_{vok} is more than doubled to 0.20 N/mm^2 at about 49% remining water. The highest initial shear strength is measured at four weeks old, with an f_{vok} of 0.38 N/mm^2 and slowly delayed drying at around 20%. With a small decrease, the initial shear strength remains high at f_{vok} 0.35 N/mm^2 eight weeks past manufacturing, when drying slowed down considerably at a level of 12%. All samples exhibited shear failure in the mortar, indicating the desired strong adhesion to the wooden surfaces.

The pattern of the initial shear strength results compared to the drying progress is as expected. As the remaining water, which acts as a solvent in the mortar formulation, is reduced, the initial shear strength increases. Once the mortar nears its equilibrium

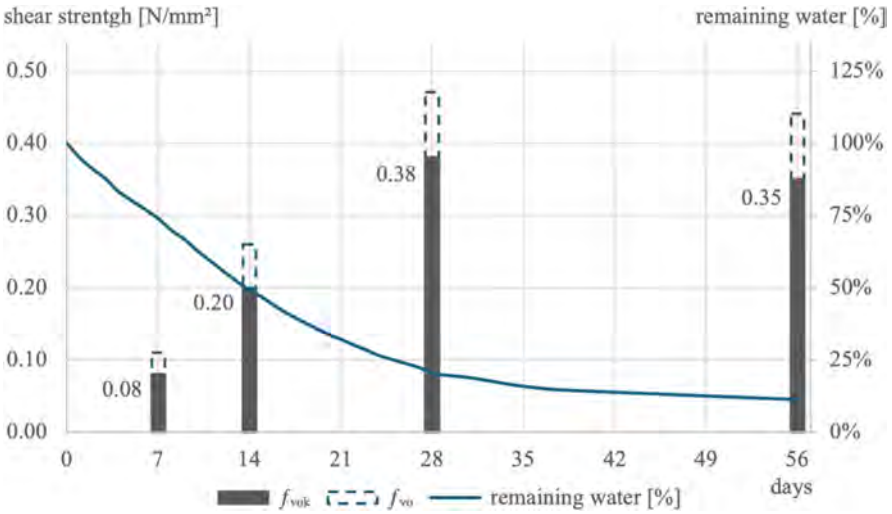


Fig. 3. Initial shear strength and drying diagram – measured values of the biobased and biodegradable mortar, day 0–56 past manufacturing, stored in a standard climate (Pracht, 2026).

moisture content and relevant parts of the water have evaporated, the development of the initial shear strength stagnates at a relatively constant level.

As expected, comparing the results from the standard setup according to DIN EN 1052–3 with f_{vok} 0.27 N/mm^2 at eight weeks, with the results from the deviating setup with lateral guidance used for the testing presented, with an f_{vok} of 0.35 N/mm^2, there is a reduction of 23% in the initial shear strength. Despite this considerable change in the results, observations during testing indicate that the lateral guidance is helpful in avoiding any kind of momentum. With the focus of this research on the development of the initial shear strength in relation to the drying process and without experience in testing a novel biobased mortar with an unknown mechanical behaviour, this decision seems reasonable. However, future testing shall be performed without any lateral guidance to ensure comparability with other mortars, strictly following the standard.

4 Conclusion

The results of this research provide initial proof of the potential of a biobased and biodegradable mortar using lupin protein as a binder, in terms of its initial shear strength. Standard testing in accordance with DIN EN 1052–3 results in an initial shear strength f_{vok} 0.27 N/mm^2 at an age of eight weeks. As this performance exceeds the minimum requirements, even for an M20 mortar with $f_{vok} \geq 0.12$ N/mm^2 according to DIN 20000–412, further research is viable.

The results further show the expected increase in initial shear strength, reaching a maximum of f_{vok} 0.38 N/mm^2 in the described setup (see sect. 2.3). Only a slight setback to f_{vok} 0.35 N/mm^2 is measured as equilibrium moisture content is approached at eight weeks.

A rather surprising finding is that, even after eight weeks of drying in a standard climate, the mortar has not reached its equilibrium moisture content. This is explained in detail in sect. 3.1. Therefore, additional research is necessary to observe the behaviour of both drying and initial shear strength beyond the eight-week timeframe, as this circumstance has not been anticipated when manufacturing the samples.

Further research carried out in parallel at the institute is looking into compressive, flexural and adhesive strength.

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Influence of Long Straw Shreds on the Compressive Performance of Lignin-Bound StrawBricks

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Abstract. The construction sector faces growing pressure to transition from resource-intensive, high-carbon materials toward sustainable alternatives. In this context, StrawBricks – compressed building blocks made from straw and lignin as a natural binder – represent a promising bio-based solution for low-rise and small-scale construction. While being developed primarily for load-bearing applications, they also show significant potential for non-load-bearing uses, such as partition walls, infill elements, or as insulation material, all of which require a sufficient mechanical performance to ensure self-supporting capacity, impact resistance, and adequate handling during processing, transport, and installation.

This study investigates whether incorporating longer straw shreds (average length ~ 50 mm) into the standard shredded straw matrix (average length ~ 15 mm) enhances compressive performance. Test specimens were manufactured under identical conditions with long shreds replacing 10%, 20%, and 30% of the short shreds. Initial stress-strain analysis revealed a pronounced increase in early-stage stiffness and compressive strength, with gains of more than 100% at a strain below 1% compared to the reference composition.

However, a critical re-evaluation using a higher preload of 54 kPa suggests that these apparent improvements are largely attributable to measurement artifacts related to preload and surface contact. Under the higher preload, the differences between compositions largely vanished, with specimens containing 10% and 20% long shreds showing no significant advantage over the reference, while the 30% composition exhibited only a transient increase in stiffness. The inconsistent response across proportions indicates that observed variations stem from experimental scatter rather than a genuine reinforcing effect.

Keywords: StrawBrick · Sustainable Building Material · Fiber Reinforcement · Lignin as Binder · Straw Construction Material

1 Introduction and Background

1.1 Relevance for a Sustainable Building Sector

The construction industry is facing crucial challenges in sustainability, driven by the urgent need to replace conventional, resource-intensive building materials. Traditional mineral building materials such as bricks and concrete, widely used across the globe,

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cause high carbon emissions due to their manufacturing processes [1], thus contributing to global warming. Moreover, they rely heavily on finite resources like sand, the scarcity of which, drives environmentally damaging extraction practices, including habitat destruction and resource depletion [2]. Furthermore, end-of-life scenarios for mineral building materials typically involve downcycling or landfilling, contributing to environmental degradation [3].

Bio-based materials are considered as promising solutions. Among them, straw is a widely available agricultural by-product with a very low environmental footprint [4]. In Germany about 20–30% of the annual straw harvest remain unused [4], offering considerable potential as a renewable resource for construction materials. Against this background a compressed building block, the so called 'StrawBrick', made from straw and lignin is developed at Bauhaus-Universität Weimar [5, 6]. Lignin is a natural polymer, obtained as a by-product of cellulose production [7], and used as a natural binder, enabling the production of a fully bio-based building material.

StrawBricks offer innovative prospects within the construction sector, particularly for small-scale, low-rise buildings. As a load-bearing material, they could serve as an alternative to traditional masonry within appropriate building classes, alleviating the demand for environmentally more harmful materials. Beyond structural applications, StrawBricks can be employed in constructing non-load-bearing walls, replacing gypsum boards and similar materials. Additionally, their integration into timber structures as infill enhances thermal insulation and energy efficiency, potentially reducing the need for supplementary insulation layers.

1.2 Objective of the Study

The compressive strength of StrawBrick is crucial for its practical application. Sufficient compressive strength is essential for use in load-bearing structures. Meanwhile non-load-bearing applications also require a certain degree of stability to ensure self-supporting capacity, impact resistance and reliable handling during transport and installation. To increase the functionality of StrawBrick, this study investigates the improvement of its compressive strength through adding longer straw shreds. Studies show that fibre reinforcements improve the mechanical performance of composite materials and that fibre length also plays a role [8, 9, 10].

The hypothesis of this study is that the addition of longer straw shreds has a similar effect as fibre reinforcement and results in better force distribution within the material matrix under load, thereby increasing compressive strength without changing the raw material input or the physical properties.

2 Methodical Approach

The groundwork for this study was laid as part of the 'StrohGold' research project at the Bauhaus-Universität Weimar. Specifically, this project established a basic material composition, which was used in this paper as a comparative reference composition. The test specimens were produced under identical conditions regarding temperature, heating duration, density, dimensions, and straw type. Shredded straw served as base material,

which in this study was partially replaced by chopped straw with longer shreds. The compressive strengths of the different compositions were then determined and compared with each other. More details on the preparation of the test specimens and the testing procedure are provided in the following.

2.1 Manufacturing Process of the Test Specimens

For the preparation of the test specimens a mixture consisting of shredded wheat straw, 8% lignin powder, and water was prepared. The water content was adjusted to achieve a straw moisture content of 20%. All proportions refer to the dry mass of the used straw. The moisture content of the straw was determined according to the method described by Krick [11]. Further details can be found in earlier studies [5], [6].

The prepared mixture was compressed in a steel mould, which was then sealed and heated at 180 °C for two hours. After cooling, the specimens were removed from the mould. The finished cubic test specimens had a bulk density of approximately 315 kg/m^3 and an edge length of 15 cm.

The main component of the mixture was shredded straw, a prefabricated product with an average fibre length of approximately 15 mm which is commonly used as blow-in straw insulation (Fig. 1a). For the reference composition (BC-00 L), only this type of straw was used. Fig. 1c shows an example of a finished test specimen.

To investigate whether a combination of short and long straw shreds could improve the compressive strength of the StrawBrick, part of the shredded straw was replaced with chopped straw in proportions of 10%, 20%, and 30%. The total amount of straw per specimen remained constant; only the ratio between short and long straw fractions was varied. The longer straw shreds were manually cut using a cutting device and had an average length of approximately 50 mm (Fig. 1b).



Fig. 1. a) Shredded straw/ short shreds; b) chopped straw/ long shreds; c) exemplary finished test specimen made from short shreds (Elert, 2024).

Table 1 provides an overview of the investigated compositions. The stated proportions refer only to the straw fraction and not to the total mixture. The measurement results presented in chapter 3 represent the average values of three specimens per mixture. An exception is composition BC-20 L, for which one specimen had to be excluded due to a measurement error; therefore, the reported values are based on the average of two specimens.

Table 1. Overview of investigated mixture compositions and relevant specimen data.

Composition name/ code?	Proportion of short shreds	Proportion of long shreds	No. of tested specimens	Mean bulk density	Storage time prior testing
BC-00 L	100%	0%	3	316 kg/m^3	5 days
BC-10 L	90%	10%	3	305 kg/m^3	7 days
BC-20 L	80%	20%	2	312 kg/m^3	7 days
BC-30 L	70%	30%	3	315 kg/m^3	2 days

2.2 Testing Procedure

Since the structural behaviour of the StrawBrick differs significantly from that of conventional mineral building materials, its maximum load and compressive strength cannot be determined using standard methods such as those specified in DIN EN 772–1. Instead, its load-bearing behaviour is more comparable to that of straw bales or, more generally, fibre-based insulation materials.

For this reason, the testing procedure applied in this study follows the principles of DIN EN ISO 29469, which specifies methods for determining the compressive properties of insulation materials. This norm is considered more suitable for materials that exhibit pronounced deformation under load before reaching failure.

However, the applied preload of 4 kPa instead of 0.25 kPa deviates from the standard and is intentionally higher. This adjustment was necessary because the comparatively higher compressive strength of the StrawBrick requires an increased preload to ensure proper contact between the bearing surface of the specimen and the testing machine. Establishing consistent contact conditions is essential to obtain reliable and reproducible measurement results.

Table 2 provides an overview of the testing procedure applied in this investigation.

Table 2. Key parameters of the testing procedure.

Compressive strength test			
Preload	4 kPa	Bearing surface area	22,500 mm^2
Displacement rate	15 mm/min	Testing machine	ZwickRoell ‘Z100/S’

3 Results and Discussion

3.1 Comparison of Measurement Results

Figure 2 presents the stress-strain curves of the compositions tested according to Table 2. All specimens incorporating long straw shreds exhibit higher stress levels compared to the reference composition (BC-00 L), particularly in the initial deformation stage

(up to approximately 0.5% compression). The stress increase is significantly steeper at low strains, indicating enhanced stiffness and load-bearing capacity at the onset of compression. This effect intensifies with increasing long shred proportion: at 1% strain for example, compressive strength increases by 60% (BC-10 L), 75% (BC-20 L), and 114% (BC-30 L) relative to the reference. However, as deformation progresses, the curves remain nearly parallel, suggesting a similar load-bearing behaviour. Consequently, the relative strength gains diminish with increasing strain, reducing to 9%, 19%, and 26% at 3% compression, respectively. These results support the hypothesis that longer straw shreds have a reinforcing effect significantly improving early-stage compressive strength in the low strain range up to approximately 3%.

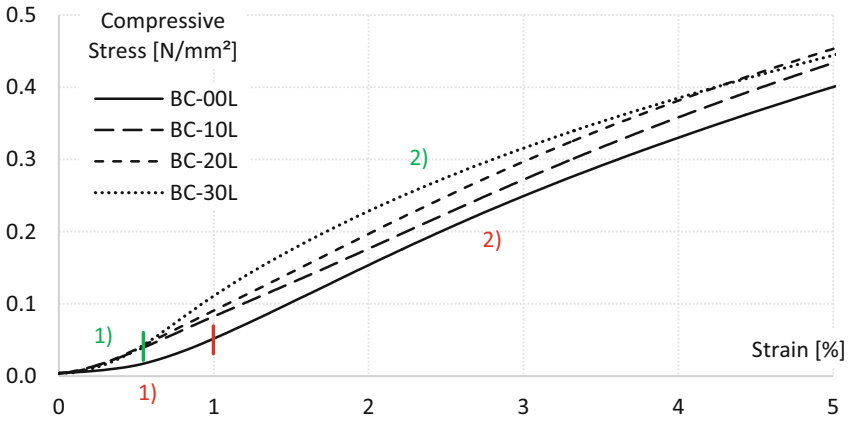


Fig. 2. Stress-strain curves of StrawBrick specimens with different straw fractions measured according to Table 2; subdivision of the stress-strain curves (marked in red and green).

3.2 Critical Evaluation of the Measurement Results

The nearly parallel stress-strain behaviour of the tested compositions raises questions regarding the true origin of the observed increase in initial compressive strength. While the enhancement is attributed to the incorporation of long straw shreds, alternative explanations cannot be entirely ruled out. Potential sources of variability include minor inconsistencies in the manufacturing process, particularly given that the reference composition (BC-00 L) was produced at a different time and by a different operator. A critical factor may be the compaction process during the manufacture: when the straw mixture is pressed into the steel mould, it may become over-compressed, potentially reducing strength in the upper portion of the specimen. Additionally, the initial preload of 4 kPa may have been insufficient to ensure full contact between the specimen surface and the testing plates, especially due to surface irregularities or protruding straw fibres. This could result in a delayed and non-uniform stress transfer, particularly in the initial phase.

Analysing the stress-strain curves they can be roughly divided into two stages (see red and green markings in Fig. 2). The first stage, characterized by a gradual stress

buildup between 0.6% and 1% strain, is followed by the second stage which exhibits a more linear response with a gradual decrease in stiffness. It is apparent that the initial phase is significantly shorter in compositions containing long shreds.

Given that the observed differences are most pronounced in the first stage and considering that this stage is highly sensitive to measurement conditions such as the potential influence of preload and surface effects, this initial region is deemed less reliable for comparative evaluation. Therefore, excluding the first stage, by applying a higher preload, allows for a more robust assessment of the material's mechanical behaviour.

3.3 Comparison with Increased Preload

To mitigate measurement uncertainties associated with the initial phase, an additional preload of 50 kPa (total preload: 54 kPa) was applied in a re-evaluation of the data. As shown in Fig. 3, this adjustment eliminates the initial stress rise, aligning the curves and removing the apparent strength advantage of the compositions with long straw shreds at low strains. Under the higher preload, BC-10 L and BC-20 L exhibit stress-strain responses nearly identical to the reference composition, indicating no significant improvement in compressive performance. Only BC-30 L exhibits higher stiffness initially, with a 34% higher stress at 1% strain, which decreases as deformation increases. At 2% strain, it is only 18% higher than that of the reference. Beyond approximately 3.5% strain, its curve intersects and falls below those of the other compositions.

The inconsistent response across the different long-shred proportions, where 10% yields a minor improvement, 20% performs slightly worse than the reference, and 30% shows a clear but transient gain, suggests that the observed differences are not systematically linked to the content of long shreds. Instead, they likely reflect the scatter of the StrawBrick. Therefore, the results do not support a consistent reinforcing effect of long straw shreds on the StrawBrick's compressive strength. The observed variations are likely attributable to random factors rather than a genuine mechanical enhancement.

The lack of a pronounced reinforcing effect may be attributed to the smooth, waxy outer surface (cuticula) of the long straw shreds, which limits mechanical interlocking and adhesion with the lignin matrix. This smooth surface reduces the ability to form effective adhesive bonds [12], thereby diminishing the load-transfer capacity between fibres and matrix. However, this issue could be addressed through surface treatments of the straw, such as mechanical abrasion, thermal activation, or chemical modification, which have been shown to improve interfacial adhesion in similar composite materials [12]. In addition, it could be investigated whether other natural fibres are better suited to improving the mechanical properties.

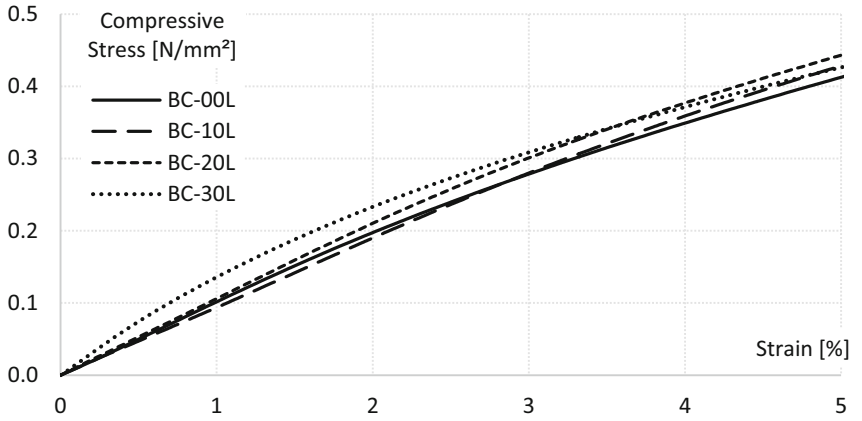


Fig. 3. Stress-strain curves excluding the initial compression (up to a stress of 0.05 N/mm^2).

4 Conclusion

This study investigated the influence of long straw shreds on the compressive performance of lignin-bound StrawBricks, with the hypothesis that longer fibres would enhance compressive strength through improved load distribution, analogous to fibre reinforcement in composites. While initial results indicated a significant increase in early-stage stiffness and compressive strength, particularly at strains below 1%, other causes for this effect could not be ruled out. Further, this effect was found to be sensitive to measurement conditions. Upon re-evaluation with an increased preload of in total 54 kPa, the apparent strength advantages of compositions containing long shreds were largely eliminated. The stress-strain responses of BC-10 L and BC-20 L became nearly identical to the reference composition (BC-00 L), while BC-30 L showed an improvement of 34% at a strain of 1% that diminished considerably with increasing deformation. The inconsistent performance across different long-shred proportions, ranging from a significant improvement to minor deterioration relative to the reference, suggests that observed differences are not systematically linked to the use of long shreds but rather reflect experimental scatter.

The lack of a consistent reinforcing effect is likely due to the smooth, waxy surface of the straw shreds and its biochemical properties, which limit mechanical interlocking and adhesion with the lignin matrix. However, the potential for improvement remains, as surface treatments such as chemical modification have been shown to enhance interfacial bonding in lignocellulosic composites. Future research should therefore focus on optimizing the straw surface to unlock the full mechanical potential of long straw shreds. In its current form, the addition of long shreds does not provide a reliable means to enhance the compressive strength of StrawBricks, but the material system holds promise when combined with appropriate surface engineering strategies.

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Specimen preparation and testing were conducted as part of a Bachelor's thesis supervised by the first author at Bauhaus-Universität Weimar by Félix Briolant (2024).

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Nanomaterials Blended Membranes for the Built Environment

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Abstract. Water and wastewater treatment is one of the key issues in the built environment. Membrane processes are effective methods for water and wastewater treatment. Fouling tendency of polymeric membranes hindered their widespread application in water and wastewater treatment. Recent research in membrane technology has been focused on nanomaterial blended polymeric membranes to reduce fouling. This study investigates nanomaterial blended polymeric membranes for sustainable water and wastewater treatment in the built environment. Polymeric membranes blended with various nanomaterials, such as zinc oxide nanoparticles and carbon nanotubes, were synthesised, characterised and tested. Membrane performance variability was evaluated by using quantitative analysis. According to the findings of this study, carbon nanotube blended membranes have the potential to improve water and wastewater treatment efficiency in built environment. In addition, consumer protection law perspective was also incorporated to address the regulatory requirements for water quality and nanomaterial safety. The interdisciplinary method promotes the responsible use of high performance membrane technologies as well as protecting consumer health and rights.

Keywords: Built Environment · Consumer Protection · Membranes · Nanomaterials · Water and Wastewater Treatment

1 Introduction

Polymeric membranes have poor mechanical, thermal, and chemical resistance while being flexible, durable, affordable, and having high separation qualities [1]. Furthermore, one of the biggest drawbacks of membrane technology is the fouling problem [2]. The amount of permeate obtained decreases as a membrane becomes fouled. In addition, membrane's separation performance decreases [3]. Fouling is caused by the accumulation of colloids, macromolecules, salts, and similar substances on the membrane surface or inside the membrane pores [4].

It was demonstrated that by reducing hydrophobic interactions between foulants and the membrane surface, i.e. increasing membrane hydrophilicity lowers membrane fouling [5–7]. Consequently, the development of inexpensive polymeric membranes with strong fouling resistance has attracted a lot of interest lately [8].

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Nanoparticles are frequently utilised as additives to enhance membrane properties in the manufacturing of fouling-resistant membranes with high permeate flux. Aluminium oxides, zirconium oxide, titanium oxide, cerium oxide, silicon oxide, and zinc oxide nanoparticles (ZnO) are a few examples [3]. Numerous studies have shown that titanium oxide nanoparticles are beneficial in reducing membrane fouling [9]. For fouling resistance, however, ZnO is a great substitute for titanium oxide nanoparticles due to its low cost and high surface-to-volume ratio. It was demonstrated that adding ZnO improves permeability and hydrophilicity of membranes [10]. Carbon nanotubes (CNT) have exceptionally high aspect ratio, strength, and stiffness [11]. CNT blended membranes have been demonstrated to have a high flux and to be more hydrophilic [12, 13].

The fabrication of membranes using nanoparticles has important implications for both environmental sustainability and consumer protection. The challenges are the stability of nanoparticle blended membranes, and the risk of nanoparticle release into treated water. In circular systems, the treated water is repurposed for both residential and commercial uses. Therefore, achieving excellent technical performance is as important as ensuring consumer protection and regulatory compliance. Thus, the aim of this study is to evaluate the performance, durability, and consumer protection effects of CNT and ZnO blended membranes.

2 Materials and Methods

CNTs were functionalised using an acid mixture prior to use, as described previously [12–14]. The membranes were prepared using the phase inversion method as described elsewhere [15–19]. N-methyl-2-pyrrolidone or N,N-dimethylformamide were used as solvents and ZnO or CNT as additives in membrane synthesis. Nanoparticles were first dispersed in the solvent and ultrasonicated for complete dispersion. The membrane solution was then obtained by adding polyethersulfone. An automatic film applicator was used to cast the resulting membrane solution onto a glass plate. The glass plate was then immersed in a coagulation bath to produce membranes. The prepared membranes thoroughly rinsed and kept in distilled water until use. Note that CNT-0 and CNT-1 denote bare and 1% CNT (with respect to polymer) containing membranes, respectively. Similarly, ZnO-0 and ZnO-2 denotes bare membrane and the membrane containing 2% ZnO (with respect to polymer), respectively.

Equation (1) was used to calculate membrane porosity (ε) by measuring the dry (w_d, g) and wet weights (w_w, g) of the membranes;

$$\varepsilon = (w_w - w_d)/(\rho \times A \times h) \tag{1}$$

where A stands for membrane area (cm^2), h for membrane thickness (cm), and ρ for water density.

A contact angle goniometer was used to measure the contact angle (CA) using the sessile drop technique. Measurement was performed after applying a 1 μL drop of distilled water on the membrane surface.

Membrane filtration tests were carried out using a dead-end membrane filtration unit for CNT blended membranes and a cross-flow membrane filtration unit for ZnO blended

membranes. Permeability and selectivity experiments were carried out at a constant transmembrane pressure of 0.5 bar. Equation (2) was used to calculate the water flux (J_w, L/m^{2}h);

$$J_w = V/(A \times \Delta t) \tag{2}$$

where V stands for the permeate volume (L) and Δt for time (h).

Protein like materials are common contaminants in water treatment, and they seriously impede membrane filtration [20–23]. Bovine serum albumin (BSA) was used as the model protein in this study. Membrane selectivity was evaluated by filtering BSA for an hour. Equation (3) was used to calculate the BSA rejection ratio (R,%);

$$R = \left(C_f - C_p\right)/C_f \tag{3}$$

where C_f stands for the BSA concentration in feed (mg/L) and C_p stands for the BSA in permeate (mg/L).

3 Results and Discussion

Addition of 2% of ZnO with respect to polyethersulfone resulted in 12% porosity increase and 7% water flux increase (Fig. 1). This increase is probably because of the hydrophilic nature of ZnO, which promotes faster solvent and nonsolvent exchange during phase inversion which probably resulted in a more open and interconnected pore structure. On the other hand, membrane porosity increased by 19% and water flux increased fourfold with CNT addition (Fig. 1). By providing low-friction pathways, CNTs enhance pore connectivity. The role of CNTs as nanoscale water transport facilitators is consistent with this increase in porosity and flux [14].

In circular water systems, adequate solute rejection is essential for consumer protection, even when permeability improvements are intended to lower energy usage. When 2% ZnO was incorporated into the membranes, both rejection and permeability increased 7% (Fig. 1). This simultaneous enhancement suggests that ZnO improves the homogeneity of pore size distribution and surface interactions with the rejected solute. The CNT blended membranes showed a significant increase in permeability, as well as BSA rejection (Fig. 1). The observed improvement in rejection rate and higher permeability demonstrates the ability of CNTs to favorably overcome the permeability-selectivity imbalance commonly encountered in polymeric membranes

Addition of nanomaterials results in substantial differences in the structure and properties of the membranes, as indicated by differences in porosity, flux, and BSA rejection, as depicted in Fig. 1. The choice of additive is of great importance in the design of membranes for circular water systems in built environment, as the properties of the membranes are largely dependent on the type of nanomaterials added.

Membranes used in circular water systems in built environment must maintain their performance and water quality over a long period. The results of this study show that the addition of ZnO and CNTs improves membrane performance compared to the bare membrane. The addition of CNTs increases selectivity and permeability drastically. On the other hand, the addition of ZnO creates a balance between rejection and permeability.

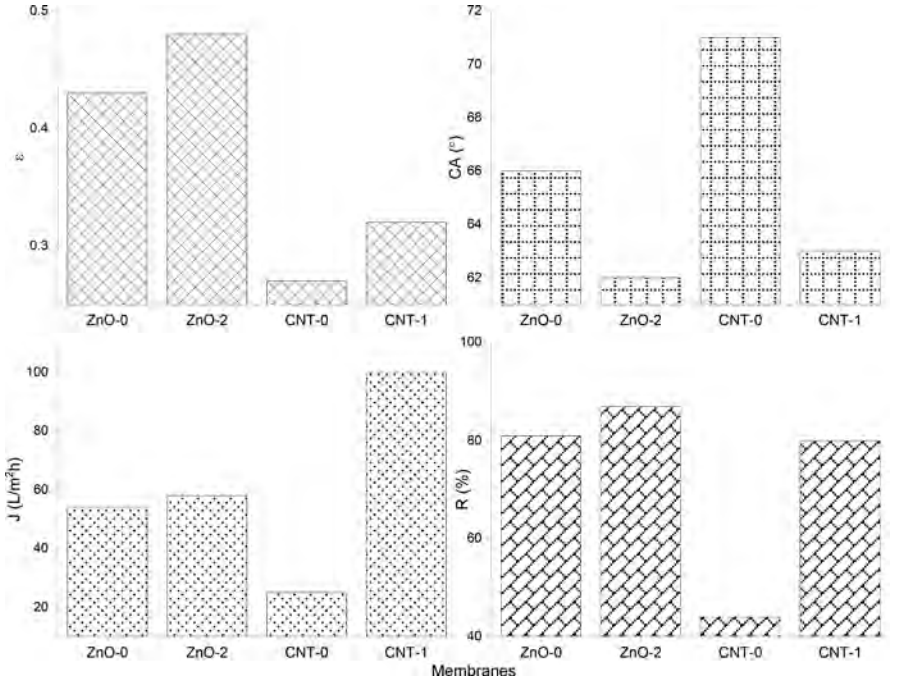


Fig. 1. Changes in porosity, contact angle, flux, and BSA rejection

Therefore, the role of nanomaterials in membrane performance should be evaluated with a holistic approach, considering long-term performance, safety, and efficiency.

The use of nanomaterials in ultrafiltration membranes for water treatment involves a clear set of rights and obligations applicable to all parties involved in the water supply chain from a consumer protection and regulatory law standpoint. According to the EU 2020/2184 directive, consumers have a fundamental right to access clean, safe, and lawful water. In return, filtration membrane manufacturers, water utilities, and system operators are obligated to ensure that new materials, including nanomaterials, do not degrade water quality throughout their service life. This includes tasks such as conducting appropriate risk assessments, preventing unwanted nanoparticle release, and guaranteeing long-term material performance in compliance with public health protection regulations.

One of the advantages of ZnO or CNT in water recycling is the higher rejection rate. However, there are some concerns about the leaching of ZnO or CNT over time, especially when water treatment systems are chemically cleaned. CNTs are tightly embedded in the polymer matrix, which severely restricts their mobility and potential for release into the treated water. CNTs have the potential to perform well even with low additive content, as demonstrated by the significant increase in permeability and high rejection rate achieved with a small amount of additive loading. For ZnO blended membranes probably material remains largely immobile in the initial stages. However, further research is needed on the long-term leaching of ZnO or CNT in water treatment systems.

4 Conclusion

The findings of the study reveal that, in comparison to bare membranes, blending ZnO or CNTs improves the efficiency of the membranes. Blending CNTs increases the selectivity and permeability, and blending ZnO balances the rejection and permeability. The CNT blended membranes are applicable in energy-efficient environments without compromising the long-term efficiency of water quality. Moreover, the strong interlocking of CNTs in the polymer matrix prevents the leakage of CNTs during the long-term usage and harsh chemical cleaning processes. Nevertheless, to ensure the safety of consumers, the long-term stability of ZnO or CNT blended membranes should be evaluated. In conclusion, the findings reveal that the nanoparticle blended ultrafiltration membranes, help to overcome the disadvantages of the conventional polymeric membranes. In this study, the significance of the selection of nanomaterials is emphasized to find a compromise between the separation efficiency and the protection of consumers. All these aspects are interconnected and play an important role in the correct application of state-of-the-art membrane technology. According to the findings of this study, CNT blended membranes have the potential to improve water and wastewater treatment efficiency in built environment.

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Towards Circular Unfired Masonry: Bio-Based Additives for Unfired Extruded Bricks

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Abstract. Ceramic masonry remains widely used due to the ease of producing extruded bricks, however, its environmental impact is high because clay must be fired. This experimental study develops extrudable, soil-based pastes for manufacturing unfired bricks/blocks as a more sustainable alternative for non-structural applications. To improve strength, the research minimized calcined binders and complemented stabilization with natural, non-calcined materials not previously explored in soil stabilization, namely oyster-shell waste and vinegar (with potential use of related industry by-products), supporting circular-economy principles. The work was conducted in two stages. In a preliminary step, soil was stabilized with varying quicklime (QL) contents and additives: marine salt (MS), calcium-enriched vinegar derived from oyster shells immersion (VS) and gypsum (G). Extruded cylindrical specimens (5 cm height, 2 cm diameter) were tested by diametral compression at 28 days under dry and saturated conditions. For dry specimens, relative to the reference mix, 10%QL increased strength by 140.3%; MS (10%QL, 3.5%MS) by 454.4%; VS (5%QL) by 723.9%; and the combined VS + MS formulation (only with 5%QL to reduce lime) achieved the highest gain, 849.1%. In stage 2, selected mixes with 5%QL, VS, MS and G were further modified with 2% cellulose/paper fibers (a paper-industry residue). Prismatic specimens (4 × 4 × 16 mm) were tested for compressive and flexural strength, water absorption and durability by immersion. The best overall performance was obtained for S_5QL_VS_3.5MS_2F, reaching 1.66 MPa at 28 days and 4.22 MPa after 365 days (with 2 months of water immersion), highlighting the potential of low-lime with bio-based materials enhanced unfired earthen units.

Keywords: Unfired bricks · Soil stabilization · Quicklime · Oyster shells · Vinegar · Durability

1 Introduction

Ceramic masonry remains a dominant construction material largely because extruded bricks are easy to manufacture and widely standardized. But, the firing stage required for ceramic production is energy-intensive and contributes significantly to CO_2 emissions [1, 2], prompting growing interest in lower-carbon alternatives. Unfired earthen materials,

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as rammed earth or compressed earth blocks (CEB) have re-emerged as a promising option, offering reduced environmental impact and compatibility with local resources and circular-economy strategies. However, despite the extruded unfired earth using the same method of production as the conventional fired brick industry, without the firing, there appear to be rare scientific articles on extruded unfired bricks or blocks [3]. In order to review this lack of research, a quantitative analysis was carried out on articles indexed on the Scopus platform using the following keywords: Unfired masonry or Unfired bricks or Unfired blocks; Unfired extruded bricks; Extruded soil bricks; Extruded earth bricks; and "Extruded earth blocks". The results confirm that there are few articles when the results are filtered specifically for extrusion (See Fig. 1). Among these, it is noted that calcined binders such as lime, but mainly cement, have been used as main stabilizing agents.

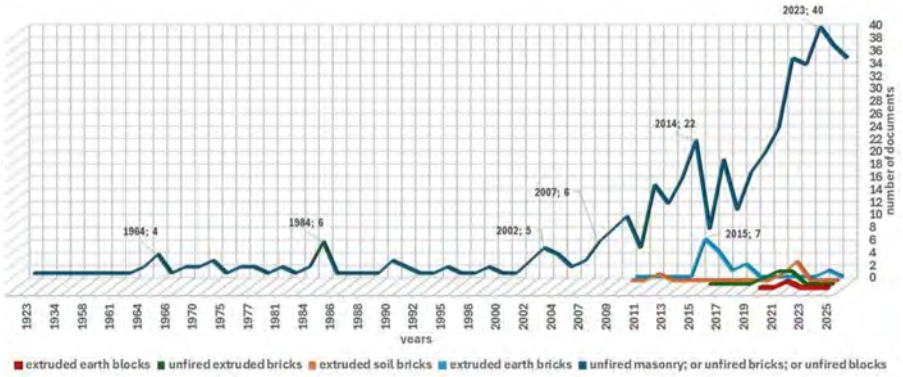


Fig. 1. Global interest in the subject under study – Quantitative analysis of scientific articles indexed in Scopus (Data from Scopus®, from Elsevier B. V, accessed on 11 March 2026).

The lack of interest in the extrusion process for unfired clay or soil may be linked to: technical difficulties in preparing samples in the laboratory; in some cases, with reduced compressive strength at higher moisture contents (potentially leading to a complete loss of structural integrity) [4]; but also, to the preconceptions still associated with earthen construction regarding its durability. Nevertheless, in 2006, the Brick Development Association formed an alliance with brick companies to develop unfired clay bricks, and they have demonstrated that these bricks can be used for domestic load-bearing walls and partitions [5]. Furthermore, the historic buildings made of raw earth that have survived and are still in use living evidence of the durability of earth as a building material. Among these, are the heritage listed by UNESCO: the "Old Towns of Djenné" and its Mosque in Mali, 3rd century BC; the "Great Wall of China", 3rd century BC to 17th century AD with rammed-earth sections; Taos Pueblo, New Mexico, from the late 13th and early 14th centuries, buildings that have withstood adverse environmental effects such as erosion caused by rain and snow, forest fires, droughts and floods; and the "Old Walled City of Shibam", Yemen, 16th-century [6]. Or ruins with preserved sections, such as the Neolithic site of Çatalhöyük in Turkey, dated to 7400–6000 BC [7].

In this study, we focus specifically on evaluating a set of natural and waste-derived additives to determine their effectiveness in stabilizing soil mixtures suitable for extrusion, aiming to reduce the amount of lime added and to test water resistance by immersion in a laboratory setting.

2 Methods

2.1 Materials and Compositions

The soil used contained: 15% clay (mainly kaolinite, as the original soil was amended with 20% kaolin due to its reduced plasticity); 13% silt; 68% sand; and 4% gravel. The experiment had two phases. At phase 1, mixtures were prepared (see Table 1) in order to evaluate: soil stabilization using quicklime, QL (applied hot, i.e. mixed directly into the soil [8]) at different percentages; incorporation of a solution of vinegar with diluted calcium from oyster shells, waste from aquaculture (by immersing the shells in vinegar 24 h before [8]) with a smaller quantity of QL to reduce the calcined material; addition of marine salt (MS) at a seawater-equivalent concentration; and gypsum addition (G) as an additive to achieve a faster hardening. The test specimens were produced by extrusion (cylinders: h = 50 mm, Ø = 20 mm) and subsequently tested by diametral compression, to evaluate the rheology of the material for the extrusion production process. The mechanical performance of the mixtures was verified through diametral compression testing, and the most promising ones were selected for subsequent stages.

Table 1. Composition of the mixtures used to produce extruded samples (cylinders)

Mix ID	Soil (g)	Quicklime (%)	Water (%)	Marine salt (%)	Vinegar Solution (%)	Gypsum (%)
S_REF	960		16.67			
S_8QL	960	8	22.92			
S_9QL	960	9	22.92			
S_10QL	960	10	22.92			
S_10QL_3,5MS	960	10	22.92	3.5*		
S_5QL_VS	960	5			22.92	
S_VS	960				16.67	
S_5QL_VS_3,5MS	960	5		3.5*	22.92	
S_10QL_1G	960	10	25.00			1
S_10QL_2G	960	10	26.04			2
S_10QL_3G	960	10	26.04			3

*Percentage of the liquid used.

At Phase 2, with a view to sustainability and performance, the new compositions were based on mixtures containing 5% of QL and VS (see Table 2), considering also the G addition. The formulations were also trialled with 2% of cellulose fibers, waste from paper kraft industry (F) to assess their physical and mechanical effect on the mixtures. And the effect of a slightly larger scale, using prismatic specimens ($40 \times 40 \times 160\,mm^3$) manually cast and rammed, given the unavailability of extrusion equipment for pieces larger than the cylinders produced.

Table 2. Composition of the mixtures used to produce compacted samples (rectangular prisms)

Mix ID	Soil (g)	Quick-lime (%)	Water (%)	Marine salt (%)	Vinegar Solution (%)	Gypsum (%)	Cellulose Fibers (%)
S_REF	1620		16.67				
S_5QL	1620	5	22.84				
S_5QL_VS_3,5MS	1620	5		3.5*	22.84		
S_5QL_3G_VS_3,5MS	1620	5		3.5*	23.46	3	
S_REF_2F	1620		16.67				2
S_5QL_2F	1620	5	22.84				2
S_5QL_VS_3,5MS_2F	1620	5		3.5*	22.84		2
S_5QL_3G_VS_3,5MS_2F	1620	5		3.5*	23.46	3	2

*Percentage of the liquid used.

2.2 Samples Preparation

The mixtures were prepared as follows: (i) Phase 1, cylinders: the soil was mixed with the binder, then water (plain or with marine salt, MS) was added. The fresh mixes were sealed in cling film and conditioned for 24 h to allow QL hydration. Specimens were produced by direct or indirect extrusion using a simplified extruder coupled to a hydraulic press (Lloyd LR 50 K Plus) (see Fig. 2a and b), at a displacement rate of 0.010 mm/s. (ii) Phase 2, rectangular prisms (Fig. 2d): moulds were filled in three layers; each one compacted with 50 blows using a metal rammer, keeping the same mass per layer to improve homogeneity. Specimens were stored at room conditions under cling film and demoulded after 5 days.

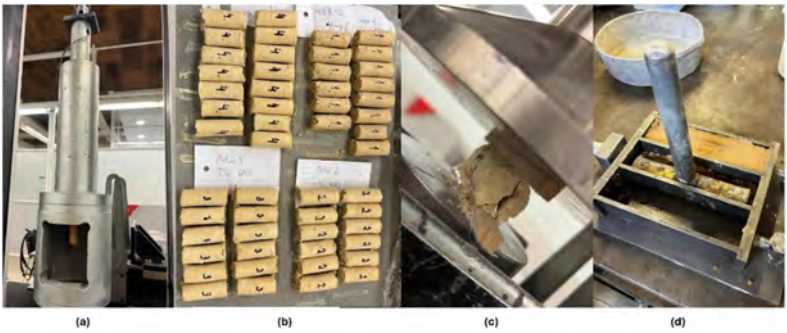


Fig. 2. Samples Preparation (a, b and c) and diametral compression test (d).

2.3 Test Methods

A diametral compression test was carried out in accordance with the NP EN 12390–6:2003 on extruded cylindrical samples (see Fig. 2c) with 28 and 60 days of curing, in both a dry and saturated state (with water immersion of 24 h). The prismatic specimens were subjected to the following tests at 28 days: flexural strength and simple compressive strength in accordance with standard NPEN 196–1 2006; water absorption by capillary action (method adapted from Hall & Djerbib [9]); and absorption by immersion (based on Australian Standard HB 195–2002), with immersion in cold water at room temperature for 24 h. And, after this last test, the specimens remained immersed for two months and left them to dry naturally for up to 360 days.

3 Results and Discussion

3.1 Phase 1: Diametral Compressive Strength of Cylindrical Specimens

The results show a marked reduction in strength when saturated (see Fig. 3, sat, in blue), indicating high sensitivity to the presence of water in all formulations. Compared to the reference mix, the addition of QL generally leads to increases in strength in the dry state and to further development between 28 and 60 days. However, mixtures containing 5% QL and VS, particularly when salt is added (MS), exhibit higher strength values in both states, despite the lower binder content. Confirming the positive effect of using QL with VS [8]. The addition of (G) also increased strength in the dry state, although not in direct proportion to the percentage added. For dry specimens at 28 days, related to S_REF: 10% of QL increased strength by 140.3%; MS with 10%QL by 454.4%; VS with 5%QL by 723.9%; and the combined VS + MS formulation (only with 5%QL) achieved the highest gain, 849.1%. The isolated effect of MS on the soil was also observed, with an increase of 231.1%.

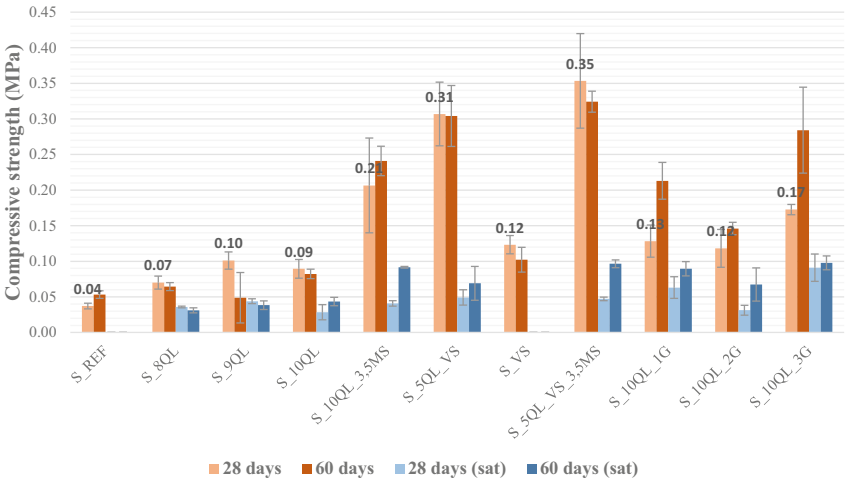


Fig. 3. Diametral compressive strength with dry and saturated extruded specimens

3.2 Phase 2: Mechanical Strength and Absorption of Rectangular Prisms

Figure 4 shows flexural and compressive strength results at 28 days, and compressive strength at 360 days for the specimens that remained intact. In general, the same trend in strength values is observed between flexural and compressive strength. Comparing mixtures without and with cellulose fibers (F) an increase is observed in general: S_REF / S_REF_2F shows +51.7%; S_5QL / S_5QL_2F +7.4%; S_5QL_VS_3.5MS / S_5QL_VS_3.5MS_2F +8.5%. The mixture with G S_5QL_3G_VS_3.5MS / S_5QL_3G_VS_3.5MS_2F decreased by 16.8%. As such, there appears to be a more positive effect of the fibers in the plain soil, without additives, reaching a better result than the soil with 5% QL at 28 days. By 360 days, the reference mixtures and the mixtures with gypsum had collapsed prior to testing, revealing susceptibility to water, contrary to what was observed in phase 1. At 360 days, a more positive effect was observed with additives showing: between S_5QL / S_5QL_2F +37.1% and between S_5QL_VS_3.5MS / S_5QL_VS_3.5MS_2F +30.7%. This confirms greater strength and durability with QL, particularly when combined with the VS solution, salt and fibers. The results are consistent with trends observed by other authors, such as the stabilizing effect of fiber [3] e the beneficial effect of quicklime on long-term resistance to produce unfired bricks [5].

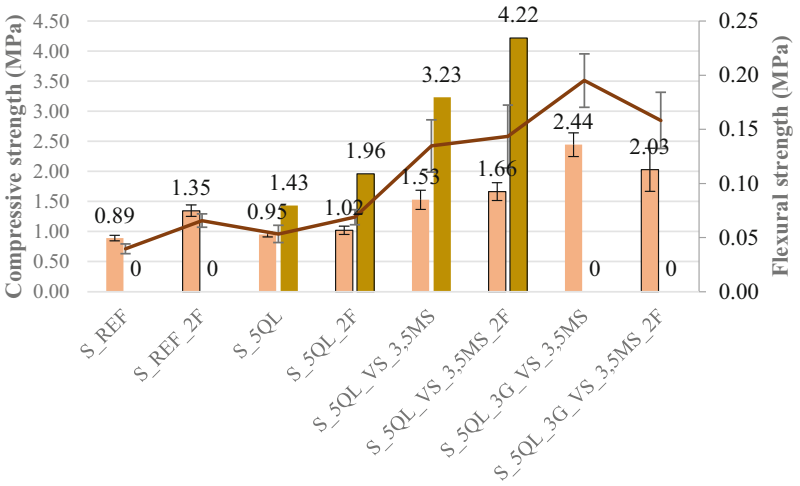


Fig. 4. Flexural and compressive strength at 28 days and compressive strength at 360 days

Figure 5 shows the results obtained for water absorption (immersion and capillarity). Contrary to expectations, the reference mixtures exhibit relatively low coefficients, observed upon the addition of fibers (S_REF_2F), although this mixture collapsed during the immersion, so these are not enough to improve the soil. The remaining mixtures already show greater consistency between the immersion and capillarity results, with a slight reduction in water absorption observed in the fiber-containing compositions. This reduction generally indicates a positive effect of fibers on controlling water absorption, whether in unstabilized or stabilized soil. Once again, the positive effect of stabilization with QL and the incorporation of VS with MS is evident, particularly with fibers. The composition with gypsum showed similar results.

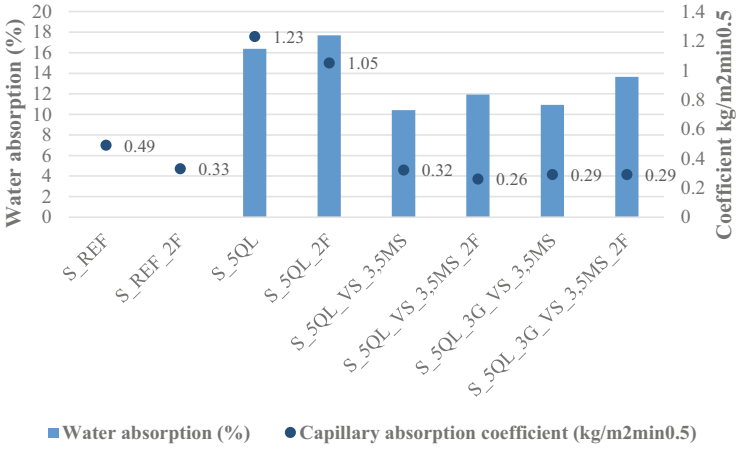


Fig. 5. Water absorption by immersion and coefficient of capillary absorption

3.3 Comparison with Performance Requirements

It is apparent that there are no specific requirements for unfired extruded bricks, particularly for non-structural applications. However, a comparison can be made by considering standards for compressed earth blocks (CEB), such as UNE41410, which specifies strength classes 1, 3 and 5 (1.3, 3, and 5 MPa) or HB195–2009, which typical values ranging from 1 to 25 MPa. However, these do not specify anything for non-structural applications. The Lehmbau Regeln, specifies for CEB or extruded earth a minimum use of class 2 (greater than 2.5 MPa on average and 2 MPa per unit) where these are subject to loads. The same applies regarding water absorption. UNE 41410 states that it is only mandatory to declare the absorption coefficient for exposed external blocks. HB195–2009 refers to a total absorption of 10 to 25%. Maskell et al. defined minimum strength criteria for unfired brick units as 2.9 MPa under 'dry' conditions (i.e. room conditions) and 1.0 MPa under 'wet' conditions (i.e. fully submerged in water for over 16 h). Whereas the values obtained from the prismatic specimens at 28 days the S_5QL_2F, S_5QL_VS_3.5MS and S_5QL_VS_3.5MS_2F range between 1.02 and 1.66 MPa. It is therefore considered more suitable for non-structural applications, although the strengths at 360 days are higher and the total absorption values fall within the mentioned limits.

4 Conclusions

The results are promising regarding stabilization with quicklime and addition of the vinegar solution containing calcium from oyster shells and sea salt, as well as the use of fibers, leading to improvements in strength and, in some cases, reduced water absorption. Although the tests show significant durability limitations in the saturated state and do not meet the minimum performance requirements for load-bearing walls, the mixtures S_5QL_VS_3.5MS and S_5QL_VS_3.5MS_2F showed satisfactory results for non-structural applications with low exposure to water. However, with accelerated carbonation after extrusion and with the application of higher loading forces during extrusion, which is normal in an industrial environment, the results might be better.

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Fire Resistance Classification of Storey-High Earth Block Walls with Varying Materials

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Abstract. Earth masonry offers a promising low-carbon alternative for load-bearing wall construction, particularly in view of the high greenhouse-gas emissions and resource consumption of the building sector. With the introduction of DIN 18940, load-bearing earth block masonry up to building class 4 has become permissible in Germany, although the fire resistance values specified in the standard remain conservative due to limited empirical data. Recent full-scale fire tests achieving REI-M 90 have demonstrated that substantially higher classifications are feasible. This study investigates the fire behavior of four wall systems constructed from extruded and pressed earth blocks with differing pore structures, moisture contents, and geometries. Comprehensive material analyses, including mercury intrusion porosimetry, permeability testing, dynamic vapor sorption, and thermal expansion measurements, were combined with standardized fire resistance tests in accordance with DIN EN 1363–1 and DIN EN 1365–1. The results show that pore connectivity, permeability, moisture transport, and drying duration strongly influence cross-sectional loss, vapor-pressure-induced damage, and residual load-bearing capacity. Walls built from extruded blocks with well-connected pores and sufficient drying periods achieved REI-M 90, while walls with low permeability or high moisture contents exhibited premature material loss and reduced mechanical stability. Overall, the findings demonstrate that earth masonry can reliably achieve high fire resistance ratings and therefore holds substantial potential for sustainable construction. The combined data provide a basis for deriving a systematic framework linking material and wall properties to fire performance.

Keywords: Fire Resistance Classification · Earth block Masonry · Load-bearing

1 Introduction

Global warming and the associated rise in greenhouse gas emissions underline the need for sustainable construction materials. In Germany, the building sector accounts for a substantial share of global greenhouse gas emissions and resource consumption [1]. Load-bearing earth block masonry offers substantial potential for this transition due to its low embodied energy, high recyclability, and regional availability [2].

With the publication of DIN 18940 [3] in 2023, load-bearing earth masonry up to building class 4 became permissible, provided that the blocks comply with DIN 18945

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[4] regarding compressive strength, moisture resistance, perforation ratio, and web thickness. Fire resistance remains a decisive criterion in this context. According to DIN 18940, plastered earth-masonry walls may be assumed to achieve REI 30 (17.5 cm) or REI 60 (24 cm), though these assumptions are conservative and based on limited empirical data.

Recent fire tests have demonstrated significantly higher performance: in 2024, a 24 cm wall plastered on one side achieved REI-M 90 for the first time in Germany, followed in 2025 by an unplastered 17.5 cm wall reaching the same classification. These results mark an important milestone for earth-masonry construction. Building on this progress, the present study investigates the thermal and mechanical behavior of different earth-block wall systems under fire exposure. The aim is to derive a systematic framework linking material properties, pore structure, moisture transport, and wall configuration to the achievable fire resistance, thereby highlighting the considerable potential of earth masonry for future sustainable building practice.

2 Materials and Methods

2.1 Materials

All specimens fulfil application class II according to DIN 18945 [4]. Blocks 001–1, 001–2, and 004 are plan-format blocks for thin-bed mortar, whereas Block 003 is a block-format block for thick-bed mortar application. Three earth mortars were used: one thick-bed mortar and two thin-bed mortars, all with an average compressive strength of 2.5 MPa and classified as A1.

A complete overview of the characteristic material properties of the investigated earth blocks is provided in Table 1.

Walls W1 and W2 were constructed using earth blocks 001-1 and 001-2 in a thin-bed application with the earth thin-bed mortar 009. The initial bedding course was constructed using fired clay blocks. Wall W1 was additionally coated on the fire-exposed side with an earth plaster mortar.

Wall W3 was built using earth block 003 and the earth masonry mortar 006 in a thick-bed application. Wall W4 was constructed from earth block 004 using the earth thin-bed mortar 023 in a thin-bed application.

Table 1. Material properties of the earth blocks examined

parameter	001–1	001–2	003	004
format (t·l·h) [mm]	240·300·250	175·327·249	240·115·113	240·248·248
average compressive strength [MPa]	6.3	6.3	6.3	5.0
void ratio [%]	27%	27%	6%	–
average bulk density [kg/m^3]	1500	1500	2000	2100
application class according to DIN 18945	II	II	II	II

2.2 Methods

Material Characterization. The pore size distribution is determined by mercury intrusion porosimetry (MIP), where mercury is forced into open pores and pore radii are calculated using the Washburn equation (see Eq. 2). As only accessible pores are detected and spherical geometry is assumed, MIP yields an approximate porosity; the effective porosity follows from bulk and true density. The resulting distribution indicates the proportions of micro-, meso-, and macropores and, together with moisture content and tensile strength, supports estimating temperatures at which vapour pressure may cause damage. MIP does not characterise continuous pore networks, which govern vapour transport under fire. This is described by permeability, which increases with connected capillaries and macropores. In the constant-head method, permeability is obtained by maintaining a steady hydraulic head and calculating the discharge using Darcy's law.

Thermal expansion is measured using a horizontal dilatometer by heating specimens to 1000 °C and recording the continuous length change. The resulting coefficient describes temperature-induced strain relevant under fire exposure.

$$p = -\frac{2\sigma \cos\theta}{r} \tag{1}$$

Large-Scale Fir Resistance Test. A wall specimen with dimensions of 3,000 mm × 3,000 mm is subjected to a standardized fire resistance test. The specimen is exposed to one-sided thermal loading in accordance with the standard temperature–time curve (ETK) specified in DIN EN 1363–1 [5]. During the exposure period, temperatures exceeding 1000 °C can be reached. The temperature–time relationship follows Eq. (1).

$$T(t) = 20 + 345 \cdot \log_{10}(8t + 1) \tag{2}$$

The fire test evaluates the criteria of loadbearing capacity (R), integrity (E), and insulation (I). Testing according to DIN EN 1363–1 [5] and DIN EN 1365–1 [6] begins after the full vertical load has been applied and maintained for 15 min.

Temperature development inside the wall is recorded by thermocouples embedded across the block thickness. The thermocouples are arranged in 20 mm intervals along the symmetry axis, at mid-height and in the upper third of the specimen. In addition, the furnace temperature and the surface temperature on the unexposed side are continuously monitored. Deformations of the wall are measured using displacement sensors, which record horizontal and vertical movements at characteristic positions on the specimen.

A mechanical impact load may be applied as an optional supplementary test in accordance with the M-criterion defined in DIN EN 1363–1. This test is carried out only if the fire resistance test has been successfully completed in accordance with the intended performance objective. An optional mechanical impact test (criterion M) may be performed if the fire test is passed. A 200 kg lead bag is released from 3 m onto the unexposed face, generating three impacts within five minutes - two under full load and one under reduced load - to assess residual mechanical stability after thermal degradation.

The structural evaluation of the walls under fire exposure is based on the effective residual cross-section at the time of observation. The eccentricity according to Eq. (3)

$$e = \frac{\Delta t}{2} \tag{3}$$

resulting from the reduced section is obtained from the geometric centre shift relative to the line of action of the applied load. The corresponding bending moment is determined using Eq. (4)

$$M = L * e \tag{4}$$

with L being the applied vertical load.

To verify whether the remaining cross-section can carry the load without tensile stresses, the core condition ("no-tension criterion") is applied. The maximum permissible eccentricity e_{max} is calculated with Eq. (5) as

$$e_{max} = \frac{t_{res}}{6} \tag{5}$$

where t_{res} is the residual wall-thickness after material loss. The corresponding limiting moment is therefore given by Eq. (6)

$$M_{e_{max}} = L * e_{max} \tag{6}$$

If $M \leq M_{e,max}$, the resultant stays within the middle third of the cross-section and the wall remains in a compression-only state. These relationships correspond to classical cross-section analysis for unreinforced masonry under combined compression and bending and provide a consistent framework for interpreting the structural behavior of the tested walls.

3 Results

3.1 Material Characterization

The mercury intrusion porosimetry (MIP) results allow classification of the pore structure into gel pores (< 0.1 µm), capillary pores (0.1–10 µm), and air pores (> 10 µm). Gel pores dominate diffusion, sorption, and moisture buffering; capillary pores govern liquid water transport and drying; air pores reduce bulk density and thermal conductivity but may decrease strength and stiffness.

Material 001 consists of 54% gel pores, 38% capillary pores, and 8% air pores. Material 003 shows a similar distribution, with 50% gel pores, 45% capillary pores, and 5% air pores, differing mainly in total pore volume (see Fig. 1). Material 004 stands out with a markedly higher air-pore fraction (41%), alongside 23% capillary and 36% gel pores.

The permeability was determined to be $5.7 \cdot 10^{-10}$ m/s for material 001, $1.7 \cdot 10^{-10}$ m/s for material 003, and $7.4 \cdot 10^{-9}$ m/s for material 004. See Table 2 for the corresponding pore-volume fractions and permeability values.

Table 2. Percentage of fine, capillary, and air pores

No.	gel pores <0,1 µm	capillary pores 0,1–10 µm	air pores >10 µm	permeability [m/s]
001	54	38	8	$5.7 \cdot 10^{-10}$
003	50	45	5	$1.7 \cdot 10^{-10}$
004	36	23	41	$7.4 \cdot 10^{-9}$

Material 001 and 003 exhibit similar fractions of capillary pores, yet their permeabilities differ markedly (see Fig. 1). This indicates that Material 001 has a more connected pore network, which facilitates faster vapor escape. Material 004 combines a high permeability with a large proportion of capillary-active pores, suggesting an even higher degree of pore connectivity.

Figure 1 plots permeability on a logarithmic scale against the volumetric fraction of capillary-active pores (> 0.1 µm).

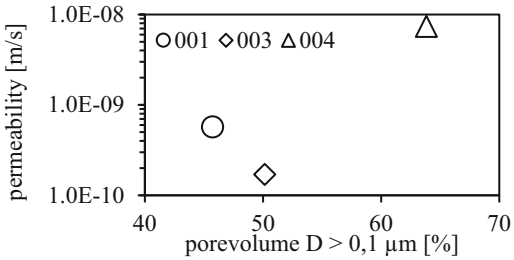


Fig. 1. Permeability vs. capillary porevolume

The thermal expansion analysis shows that Material 001 does not expand up to 250 °C but contracts, with an average length reduction of −0.23%. In contrast, Material 003 exhibits a slight expansion of 0.1%. The corresponding mean curves are shown in Fig. 2. No data are available for Material 004, as a suitable specimen could not be extracted in sufficient quality from the block.

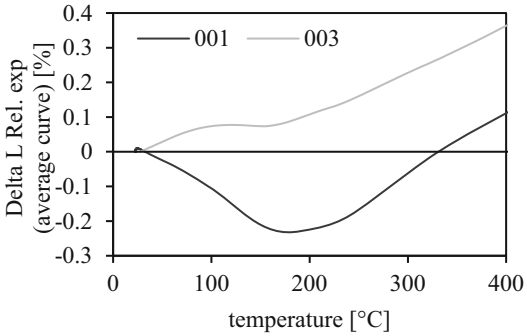


Fig. 2. Thermal expansion in the temperature range up to 400 °C

3.2 Large-Scale Fire Resistance Test

The four wall specimens, constructed from the earth blocks and mortars described in the Materials section, exhibited distinct thermal and mechanical behaviors during the fire resistance tests, reflecting their different geometries, moisture contents, drying periods, and loading conditions. The load and utilization factor were calculated in accordance with Eurocode 6 [7]. According to DIN 18940, higher utilization factors result.

Wall W1, a plastered thin-bed masonry wall with 24 cm perforated plan blocks, had an initial moisture content of 10.8 M-% after a 28-day drying period and was loaded with 840 kN (64% of its maximum load capacity). Early plaster detachment occurred after seven minutes, followed by explosive spalling between 100 and 250 °C. Similar behaviour has also been reported for concrete [8, 9].

After a cross-sectional loss of about 2 cm, the resulting eccentricity e = 12.5 mm (Eq. 3) remained well below the permissible e_{max} = 35.8 mm (Eq. 4), and the corresponding bending moment M = 10.5 kNm (Eq. 5) also remained below its limiting value $M_{e,max}$ = 30.1 kNm (Eq. 6). The subsequent mechanical impact test (200 kg lead bag, 3 m drop height) confirmed the stability of the wall, allowing a classification of REI-M 90.

Wall W2, an unplastered 17.5 cm thin-bed masonry wall, had an initial moisture content of 2.4 M-% after 52 days of drying and carried a vertical load of 570 kN, which is 50% of the maximum load capacity. The wall showed no spalling, cracking, or deformation throughout the fire exposure and withstood all three impact loads without impairment. It achieved a classification of REI-M 90.

Wall W3, a 24 cm thick-bed masonry wall built from block-format blocks, had a moisture content of 1.7 M-% after a 27-day drying period and was subjected to 840 kN (64% of its maximum load capacity). After approximately 16 min 30 s, a 3 cm surface layer detached at about 100 °C, in line with the depth of the elongated internal void. Continued heating caused further material loss, resulting in an estimated cross-sectional reduction of 6–8 cm. The corresponding eccentricity e = 30–40 mm exceeded the permissible e_{max} = 26.7 mm, and the associated bending moments M = 25–34 kNm surpassed the limiting moment of $M_{e,max}$ = 23 kNm. These estimated values provide a

coherent explanation for the observed reduction in structural capacity, and the wall met the fire resistance requirements up to REI 30.

Wall W4, constructed from unperforated 24 cm plan blocks in thin-bed construction, had an initial moisture content of 3.1 M-% after a 27-day drying period and carried 603 kN (58% of maximum capacity). The wall exhibited strong vapor release during heating. A 5 cm surface layer detached between 24 and 25 min at around 200 °C, followed by additional material loss at 39 min and subsequent collapse. The estimated cross-sectional reduction (5–8 cm) resulted in eccentricities of e = 25–40 mm, close to or exceeding the admissible e_{max} = 31.7 mm, and the bending moments M = 15.1–24 kNm approached the limiting value of $M_{e,max}$ = 27 kNm. These estimated relationships are consistent with the observed progression of damage, and the wall fulfilled the fire resistance requirements up to REI 30.

The following Table 3 provides a summary of the eccentricity e resulting from the cross-sectional loss, the bending moment M, the maximum eccentricity e_{max}, and the maximum permissible bending moment $M_{e,max}$.

Table 3 Key values for eccentricity and bending moment capacity

No.	e [mm]	M [kNm]	e_{max} [mm]	$M_{e,max}$ [kNm]
W1	12.5	10.5	35.8	30
W2	0	–	–	–
W3	30–40	25–33	26.7	23
W4	25–40	15–24	31.7	27

4 Conclusion

Walls W3 and W4 failed due to loss of load-bearing capacity caused by extensive cross-sectional loss and the resulting eccentricity, whereas W1 and W2 remained stable. These differences can be explained by the material analyses. In W1, the plaster led to increased moisture content and vapor pressure, causing detachment of the outer web. Damage ceased at an early stage, likely due to enhanced evaporation through exposed perforations and the presence of a denser outer skin only at the inner void surfaces. The pore structure and permeability of Material 001 indicate good pore connectivity, while thermal expansion does not introduce additional stresses.

W2, constructed from the same material, remained unaffected. This behavior is attributed to its significantly lower moisture content after prolonged drying and to favorable moisture transport properties, highlighting the importance of sufficient drying prior to testing.

In W3, material loss occurred in thicker flakes (≈3 cm), resulting in a greater reduction than in W1. Despite a high capillary pore fraction, low permeability indicates limited pore connectivity, restricting vapor escape and promoting pressure build-up. Failure

occurred near elongated perforations, which likely acted as structural weak zones. W4 exhibited a different damage mechanism. Although permeability is high, substantial material loss still occurred, suggesting that vapor pressure was not the sole governing factor. In the absence of thermal expansion data, its influence cannot be excluded. A moving interface between dry and moist zones may also have contributed to detachment.

Overall, the results indicate that a pore structure combining a high proportion of gel and capillary pores with sufficient permeability is favourable for fire resistance. A higher void ratio increases the evaporation surface and shortens transport paths, thereby facilitating moisture release and contributing to reduced damage.

The findings demonstrate that earth masonry can achieve REI-M 90, provided that pore structure enables effective vapor release, moisture content is low, and cross-sectional loss remains limited. The combined analysis of pore structure, permeability, moisture transport and thermal expansion reveals clear links between material properties and fire performance, underscoring the potential of earth masonry as a robust and sustainable construction system.

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Use of Lightweight Thermal Insulation Materials Promoting Inclusivity in Construction Workforce

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Abstract. This paper examines the theoretical relationships between sustainable lightweight construction materials developed within the SNUG project "Circular Economy Based Materials Development to Foster The Transition to Sustainable and High-Energy Performance Buildings at Optimal Costs" and workforce accessibility in the building sector, with particular attention to ergonomic and gender inclusion dimensions. The study analyses four material innovations evaluating how their physical and installation characteristics may influence the demands placed on construction workers: aerated eco-concrete blocks, self-levelling mortars incorporating phase change materials, aerogel-based insulation and plasters, and bio-based hemp fibre panels. The methodology is literature-based and analytical, drawing on established ergonomics principles, material performance data, and workforce research to identify plausible pathways through which reduced material weight and technically sophisticated installation processes could lower physical barriers and broaden workforce participation. Results indicate that SNUG materials collectively shift installation emphasis from physical strength toward technical knowledge, precision, and equipment operation, though empirical validation remains absent. The paper concludes that the transition to sustainable construction presents an opportunity to intentionally integrate social and environmental goals, while cautioning against premature claims.

Keywords: Lightweight Construction Materials · Ergonomics · Construction Workforce Inclusion · Sustainable Insulation · Biobased Materials · Circular Construction

1 Introduction

The construction sector is undergoing a profound material transition driven by climate commitments, circular economy principles, and the imperative to reduce the embodied energy and carbon footprint of buildings. Alongside these environmental imperatives, the sector faces longstanding challenges of workforce diversity and inclusion, with women and workers of varying physical capabilities remaining significantly underrepresented,

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particularly in site-based roles. Lightweight sustainable insulation materials, such as those developed within the SNUG Horizon Europe project, offer thermal performance and environmental benefits that are increasingly well documented; however, their potential implications for the physical demands of construction work, and by extension for workforce accessibility, have received comparatively little scholarly attention. This paper addresses that gap by examining the theoretical relationships between the physical and installation characteristics of four SNUG material innovations, namely aerated eco-concrete blocks, self-levelling mortars incorporating phase change materials, aerogel-based insulation and plasters, and bio-based hemp fibre panel, and the ergonomic and inclusion dimensions of construction workforce participation.

2 Methodology

This study employs a structured narrative literature review, followed by an analytical framework that maps material performance characteristics of SNUG project innovations onto ergonomic and workforce inclusion dimensions. Together, these two components enable the identification of theoretically grounded pathways linking material innovation to social sustainability outcomes, while maintaining transparency regarding the absence of empirical field data.

2.1 Literature Review

The literature review was guided by two research questions: (a) in what ways do lightweight materials contribute to ergonomic solutions for diverse employee needs in the construction industry? and (b) in what ways can the use of lightweight thermal insulation materials promote inclusivity in construction workforce training programmes? Literature was identified through the ScienceDirect AI-assisted discovery tool (now LeapSpace), queried directly with the two research questions stated above. This approach does not constitute a formal systematic review and does not guarantee exhaustiveness or full reproducibility of results, as repeated queries with the same questions may return partially different sets of sources; however, it provides a sufficiently representative body of evidence for the analytical purposes of this paper, which is theoretical rather than empirical in nature. Sources were selected on the basis of direct relevance to the two research questions, and the findings are synthesised in Tables 1 and 2.

Table 1. Ergonomic Contributions of Lightweight Materials

Ergonomic Aspect	Lightweight Material Contribution	Supporting Citations
Reduced physical strain	Easier handling, transport, and installation	[1–5]
Adaptability	Modular/prefab systems, suitability for diverse worker profiles	[1, 3, 6, 7]
Enhanced safety	Lower injury risk, supports ergonomic equipment use	[1, 3, 6, 8, 9]

(*continued*)

Table 1. (*continued*)

Ergonomic Aspect	Lightweight Material Contribution	Supporting Citations
Integration with technology	Enables lightweight ergonomic monitoring systems	[10–13]
Customization and sustainability	Use of local/recycled materials, ergonomic product design	[1, 6, 9]

Table 2. Key Features Promoting Inclusivity

Feature	Impact on Inclusivity in Training Programs	Supporting Citations
Reduced material weight	Easier handling and installation for diverse trainees	[14–17]
Use of recycled/waste inputs	Training in sustainable, innovative practices	[14, 16, 20]
Improved workability	Accessible for trainees with varying skill levels	[18]
Prefabrication potential	Less reliance on heavy equipment, broader participation	[17, 19]
Cost savings	More accessible training due to lower project costs	[17, 20]
Need for strength and insulation balance	Standardized, inclusive curriculum development	[15, 18]

2.2 Analytical Framework

The analytical component maps the documented physical and installation characteristics of four SNUG material innovations onto two established dimensions of workforce accessibility: physical barriers and skills transition. For each material, available technical data, including density, weight per unit, installation technique, and equipment requirements, were extracted from SNUG project documentation [21] and contextualised against ergonomic principles and workforce research identified in the literature review.

The physical barriers dimension assesses how material weight and handling demands compare to conventional equivalents, drawing on the ergonomics literature linking cumulative load to musculoskeletal injury risk.

The skills transition dimension evaluates whether material installation shifts emphasis from physical strength toward technical knowledge, equipment operation, or precision-based tasks. Together, these dimensions provide a structured basis for identifying logical theoretical pathways through which material innovation might broaden workforce participation, while maintaining appropriate epistemic caution in the absence

of empirical field data. No statistical meta-analysis was conducted, as the heterogeneity of study types and the absence of primary workforce data precluded such an approach.

3 Results

3.1 Lightweight Materials and Construction Workforce Inclusivity

Lightweight materials, including lightweight concrete, engineered cementitious composites (ECC), composite panels, and foam concretes enhanced with biobased admixtures, significantly reduce the dead load of building elements, making them easier to handle, transport, and install on construction sites. This weight reduction directly lessens physical strain on workers, offering a critical ergonomic advantage for tasks involving repetitive lifting, carrying, or assembly, while accommodating a broader range of physical capabilities and reducing the risk of work-related musculoskeletal disorders. Beyond individual ergonomic benefits, lightweight thermal insulation materials support wider workforce inclusion by lowering physical barriers to participation, enabling cost savings in transportation and training, and aligning construction practice with sustainable and circular economy principles, collectively creating conditions for broader and more diverse workforce engagement.

3.2 Workforce Implications of SNUG Material Characteristics

Aerated Eco-Concrete Blocks: The SNUG aerated eco-concrete blocks represent a significant advancement in sustainable masonry, achieving densities of 420–441 kg/m^3 through complete replacement of ordinary Portland cement with ground granulated blast furnace slag activated with lime and calcium carbide slag. These blocks demonstrate compressive strengths comparable to conventional autoclaved aerated concrete while maintaining thermal conductivities in the range of 0.111–0.119 W/(m·K) [21]. From a workforce perspective, the density reduction compared to conventional concrete blocks (typically 600–1800 kg/m^3) is noteworthy. A standard block measuring 200 × 200 × 400 mm at 1500 kg/m^3 weighs approximately 24 kg, while an equivalent SNUG block at 430 kg/m^3 weighs approximately 6.9 kg. This substantial weight reduction could influence the physical demands of masonry work, particularly in high-rise construction. The established ergonomics principle that lighter materials reduce cumulative physical load creates a plausible pathway through which this innovation might indirectly support workforce accessibility, though empirical workplace studies would be required to confirm this.

Self-Levelling Mortars with Phase Change Materials: SNUG's self-levelling mortars incorporating phase change materials (PCMs) for thermal energy storage [21] fundamentally alter the physical nature of floor preparation. Their high fluidity allows autonomous spreading across subfloors with minimal manual finishing, shifting the skill emphasis from sustained physical trowelling, which is a repetitive motion contributing to musculoskeletal disorders, towards proper mixing, temperature control, and timing. SNUG project documentation confirmed workability similar to or better than commercial reference mortars, with positive feedback from installation workers at the Norway

demonstration site. The incorporation of PCMs introduces technical complexity requiring understanding of phase change temperatures and thermal behaviour, which may favour workers with technical training over those selected primarily for physical capability. The bio-based formulations using coconut oil in biochar matrices further emphasise material science knowledge, though floor installation still involves significant physical demands including material transport and awkward postures; whether the overall balance of demands shifts sufficiently to influence workforce composition would require comparative ergonomic assessment.

Aerogel-Based Solutions: Aerogel materials possess the lowest thermal conductivity of any solid material due to their nanoporous structure containing up to 99.8% air, resulting in extreme lightweight properties. The SNUG project has developed two primary applications: blown-in insulation using recycled aerogel waste and aerogel-enhanced lime plasters for building envelopes [21]. The blown-in application shifts physical demands from lifting and fitting to equipment operation, hose management, and quality control. The material, formulated from commercial aerogel waste (Agitherm) or construction and demolition waste (CDW), is exceptionally light, though equipment and hose systems still require physical handling. The aerogel-enhanced lime plasters similarly emphasise application technique over material handling strength, incorporating CDW-based aerogel granules to achieve comparable thermal performance while maintaining the technical skill requirements of the lime plastering trade. These applications illustrate a broader pattern: as materials become more technically sophisticated, installation increasingly emphasises knowledge, precision, and equipment operation alongside physical strength. However, whether this influences workforce composition depends on how companies structure work and allocate tasks.

Bio-Based Panels: The SNUG bio-based panels, manufactured from hemp fibres bonded with tannin-based natural adhesives, achieve thermal conductivity below 0.055 W/(m·K) while maintaining densities of 190–300 kg/m^3 under laboratory conditions. Under industrial production conditions, panels are manufactured at 250–350 kg/m^3, consistent with hemp-based construction materials in the literature [22]. Large-format panels (18 × 1830 × 3660 mm) have a mass ranging from approximately 30 kg (at 250 kg/m^3) to 42 kg (at 350 kg/m^3), and their use reduces the number of joints, mechanical fasteners, and installation time per m^2. A laboratory-scale panel (1000 × 1000 × 50 mm) at 300 kg/m^3 weighs approximately 15 kg, significantly lighter than equivalent conventional panels [21]. Installation involves cutting to fit, mechanical or adhesive attachment, and render finishing, emphasising precision over heavy lifting, with the light weight being particularly advantageous at height or in confined spaces.

4 Discussion

4.1 Physical Barriers

The most direct potential pathway towards workforce accessibility connects material weight to physical accessibility. Construction work involves repetitive lifting, carrying, and positioning of materials, often in awkward postures or at height; cumulative load

over a work shift is a significant predictor of musculoskeletal injury and fatigue. If sustainable materials systematically reduce unit weight without proportionally increasing other physical demands, they could theoretically lower barriers for workers with less upper body strength, a characteristic that shows population-level gender variation. This pathway assumes physical strength requirements represent a genuine barrier to construction participation. Research on women in construction indicates that while physical demands are frequently cited, they interact with other factors including lack of appropriate equipment, poor workplace ergonomics, inadequate training, and social expectations. Physical capability varies more within genders than between them, and the question is whether population-level differences create statistical disparities in recruitment, retention, or injury rates that material innovations might reduce. This is a question that would require empirical study to confirm.

4.2 Skills Transition

A second potential pathway towards workforce accessibility involves the changing skill profile associated with sustainable material installation. The SNUG materials collectively introduce several technical complexities: understanding phase change temperatures in PCM mortars, managing self-levelling properties and rapid setting times, operating blown-in insulation equipment, handling aerogel granulates that require care to maintain performance, and applying bio-based materials with specific moisture and temperature considerations. If these requirements shift emphasis toward technical knowledge and scientific understanding relative to physical strength, they might attract different candidate pools. However, this depends on whether training programmes adapt, whether employers value these technical skills in hiring decisions, and whether such training is genuinely more accessible than strength-based selection.

5 Limitations

The inclusion benefits proposed in this paper are theoretical and require empirical validation, as no workforce composition data, ergonomic assessments, or training outcome studies are currently available for SNUG materials. Physical demands represent only one of many barriers to women's participation in construction, with harassment, discrimination, lack of mentorship, and pay inequity frequently cited as more significant obstacles. Emphasising gender differences in physical capability risks reinforcing stereotypes, as capability varies more within genders than between them. New materials may moreover create new barriers while reducing others, and outcomes ultimately depend on a broader system of hiring practices, training availability, union policies, cultural attitudes, and policy interventions.

6 Conclusions

The SNUG sustainable insulation materials, namely lighter eco-concrete blocks, large-format bio-based panels, equipment-oriented aerogel applications, and self-levelling mortars, create logical theoretical connections between material innovation and workforce accessibility, potentially lowering physical barriers while advancing environmental

goals. However, the gap between theoretical possibility and demonstrated impact is substantial, and claiming that these materials effectively support gender inclusion would be premature without empirical research on workforce composition, ergonomic demands, and training outcomes. The transition to sustainable construction nonetheless presents a genuine opportunity to intentionally integrate social and environmental goals, advancing multiple sustainability dimensions simultaneously.

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Urban and Regional Perspectives: Circular Cities, Heritage Regeneration, and Urban Mining

Reviving Prodromos Village Through Adaptive Reuse

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Abstract. Adaptive reuse is a vital sustainability strategy supporting environmental conservation, cultural continuity, and socio-economic regeneration. While widely explored in urban contexts, its role in rural settlements remains underexplored. This paper investigates adaptive reuse for rural regeneration through a case study of Prodromos village and the abandoned Verengaria Hotel in Cyprus. The research adopts a qualitative, design-led methodology integrating literature review, contextual analysis, and exploratory spatial inquiry. The Adaptive Reuse Potential (ARP) model is applied conceptually to assess reuse suitability and regeneration capacity. Two scenarios are comparatively evaluated: the adaptive reuse of the Verengaria Hotel as a wellness and cultural hub, and the development of an Agricultural Education and Cultural Centre. The findings suggest that adaptive reuse can function as a multi-scalar socio-spatial strategy linking heritage preservation, tourism, agriculture, education, and community resilience. The study proposes a design-led framework to inform sustainable rural regeneration in comparable mountainous and peripheral contexts.

Keywords: Adaptive Reuse · Rural Regeneration · Heritage Conservation · Social Sustainability · Design-Led Research · Sustainable Architecture

1 Introduction

Adaptive reuse is a key strategy in sustainable architecture and circular construction, extending building lifespan while reducing embodied energy, material waste, and environmental impact [1, 2]. While widely applied in urban areas, its potential in rural settlements remains underexplored despite growing challenges of depopulation, ageing populations, and economic decline across Europe and the Mediterranean [3]. In these contexts, the abandonment of historically significant buildings coincides with the loss of socio-economic anchors, even though rural areas retain strong environmental and heritage value.

Beyond its environmental rationale, adaptive reuse operates as a socio-spatial strategy linking environmental stewardship, cultural continuity, and social resilience [4]. It aligns with circular economy principles by treating existing buildings as material resources rather than obsolete structures, reducing resource-intensive demolition and reconstruction. As Elefante [5] argues, "the greenest building is one that is already built."

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This paper investigates adaptive reuse as a multi-scalar rural regeneration strategy through the case of Prodromos village and the abandoned Verengaria Hotel in Cyprus. It explores how adaptive reuse can activate architectural heritage, agricultural landscapes, and community infrastructure through two design-led scenarios: (i) the transformation of the Verengaria Hotel into a wellness and cultural hub linked to ecotourism, and (ii) a multifunctional Agricultural Education and Cultural Centre combining sustainable agriculture, learning, and community engagement.

Methodologically, the research adopts a qualitative, design-led approach based on literature review, contextual analysis, and spatial investigation. The Adaptive Reuse Potential (ARP) model [2] is used conceptually to assess regeneration capacity, with proposals evaluated across environmental, social, economic, heritage, and spatial dimensions to reframe reuse into a multi-scalar framework for rural regeneration.

2 Methodological Framework

The research adopts a qualitative, case-based methodology integrating literature review, contextual analysis, and design-led inquiry to investigate rural heritage environments where socio-spatial relationships transcend quantitative metrics [4, 6]. Design-led research is employed as an analytical method of inquiry to spatially test and critically interpret theoretical sustainability principles [7, 8]. The methodology follows four interrelated stages:

Stage 1: Theoretical and Literature Review. A critical review establishes the conceptual framework, focusing on embodied energy conservation, material reuse, and social sustainability [6]. The Adaptive Reuse Potential (ARP) model [2] is adopted conceptually to evaluate reuse suitability based on physical condition, functional obsolescence, heritage significance, and socio-economic context [6].

Stage 2: Contextual and Site Analysis. This stage examines Prodromos village and the Verengaria Hotel through archival data, demographic analysis, policies, field observations, and secondary literature to investigate climatic conditions, settlement morphology, agricultural history, and spatial abandonment [6].

Stage 3: Design-Led Scenario Development. This stage utilizes exploratory spatial scenarios developed within an academic studio framework [6]. Operating as investigative tools, the proposals translate sustainability principles into spatial and programmatic interventions to activate underutilised architectural and landscape assets [6].

Stage 4: Evaluation and Comparative Assessment. The final stage evaluates the design scenarios against environmental, social, economic, heritage, and spatial sustainability criteria derived from adaptive reuse literature to assess their capacity to support long-term resilience [6]. The established evaluation matrix and its corresponding qualitative criteria are outlined in Table 1.

Table 1. Evaluation Criteria

Sustainability Dimension	Evaluation Criteria
Environmental Sustainability	Reuse of existing structures, embodied energy conservation, minimal landscape disturbance, ecological integration
Social Sustainability	Community interaction, cultural continuity, public accessibility, social activation
Economic Sustainability	Tourism diversification, employment opportunities, year-round activity, local economic support
Spatial Integration	Connectivity with village fabric, pedestrian accessibility, landscape integration
Heritage Preservation	Retention of architectural identity, preservation of historical significance
Rural Resilience	Population retention potential, support for local production, long-term adaptability

3 Application of the ARP Model

To strengthen the analytical framework, the Adaptive Reuse Potential (ARP) model developed by Langston et al. [2] is applied conceptually to the Verengaria Hotel and the wider Prodromos settlement. The ARP model evaluates reuse suitability through a combination of physical, functional, environmental, and socio-economic indicators. Although this study does not undertake a full quantitative ARP calculation, the model provides a structured framework through which the reuse capacity of the site can be critically assessed. A conceptual breakdown of these evaluation factors applied to the study area is provided in Table 2.

Table 2. Application of the ARP Model

ARP Assessment Factor	Evaluation of Verengaria Hotel and Prodromos
Physical Condition	Structurally deteriorated but recoverable through restoration and adaptive intervention
Heritage Significance	High architectural, historical, and symbolic value within Cypriot mountain heritage
Functional Obsolescence	Original hospitality model no longer economically viable in its former form
Environmental Context	Strong climatic and landscape advantages supporting ecotourism and wellness activities
Community Value	Strong local identity and collective memory associated with the hotel and village

(*continued*)

Table 2. (*continued*)

ARP Assessment Factor	Evaluation of Verengaria Hotel and Prodromos
Spatial Connectivity	Strategic relationship between the hotel, village centre, agricultural land, and natural landscape
Economic Potential	Opportunities for tourism diversification, agricultural education, and cultural programming

The assessment indicates that, despite prolonged abandonment and physical deterioration, the Verengaria Hotel retains high adaptive reuse potential due to its symbolic significance, spatial position, environmental qualities, and capacity to accommodate diversified functions. The analysis also demonstrates that adaptive reuse in rural contexts extends beyond individual buildings and must be understood in relation to broader settlement systems, landscape networks, and community infrastructures.

4 Design-Led Regeneration Framework

Prodromos is located in the Troodos mountain region of Cyprus at approximately 1,380 m, making it the highest village on the island. Its development has historically been shaped by agriculture, forestry, and mountain tourism, supported by its climatic conditions and natural landscape, with apple cultivation enabled by the 1962 Prodromos Dam historically playing a significant role in the local economy. The settlement is divided between Lower Prodromos, characterised by its traditional village fabric, and Upper Prodromos, where the Verengaria Hotel is located. Designed by British architect Walter Henry Clarke and completed in 1931, the hotel functioned as a prominent mountain resort and cultural landmark until changing tourism patterns, economic decline, and management difficulties contributed to its closure in 1984, coinciding with broader processes of depopulation and service decline within the village. Despite its abandonment, the Verengaria Hotel remains a significant architectural and cultural asset with strong symbolic value; together with underutilised agricultural land, vacant buildings, and declining public spaces, the area presents a landscape of latent environmental, cultural, and spatial resources—including orchards, forest systems, historic architecture, and walking routes—within which this study proposes a design-led framework for rural regeneration, treating the built fabric as an integrated socio-spatial system operating through two complementary regenerative strategies.

4.1 Wellness, Nature and Cultural Regeneration

This first design-led research scenario positions adaptive reuse as a heritage- and tourism-led strategy, testing it as a catalyst for rural regeneration in high-altitude, depopulating contexts by using the abandoned Verengaria Hotel as a case study. This intervention puts into practice core principles of adaptive reuse, heritage conservation, and social sustainability within a concrete spatial and programmatic framework. To achieve this, environmental performance, social activation, and economic viability criteria are translated

into spatial strategies, reprogramming the historic hotel structure into a multi-functional wellness, cultural, and leisure facility to evaluate how its unique mountain architecture can accommodate contemporary uses while retaining cultural meaning.

Landscape integration forms a critical spatial component of this model. Minimal-intervention pedestrian pathways are woven through the topography to link indoor programmatic functions directly with outdoor ecotourism activities, prioritising continuity with existing vegetation and expanding the architectural intervention well beyond the building envelope. These outdoor recreational zones assess whether the deliberate activation of natural assets enhances local economic and social impacts while preserving the underlying ecological integrity of the mountain landscape.

At the settlement level, complementary interventions extend the strategy into the traditional fabric through the adaptive reuse of existing village buildings. This includes transforming the former municipal school into an educational space and introducing a new cultural facility near the Church of Saint John the Forerunner (the Forerunner), enabling an assessment of how diverse building typologies support education, heritage interpretation, and community engagement. This approach is tied to reinstating the central village square with everyday services and small-scale commerce to actively stimulate public life, test links between architectural reuse and pedestrian connectivity, and evaluate whether improved amenities can support population retention. Overall, this proposal demonstrates how rural reuse can be systematically tested as a multi-scalar strategy, producing evidence-based insights on environmental performance, cultural continuity, and socio-economic resilience.

4.2 Agricultural Education and Cultural Centre

The second strategy approaches adaptive reuse as a productive landscape model, examining how programmatic diversification can support rural regeneration through sustainable agriculture, education, and cultural production. Using Prodromos village and the underutilised land around the Verengaria site as a testing ground, it explores agriculture as a socio-spatial system capable of reinforcing community resilience, knowledge exchange, and population retention in depopulating rural contexts. The project explicitly translates theories of social sustainability and rural development into an integrated spatial and organisational campus layout, testing whether heritage structures and vacant terrain can successfully host contemporary educational, productive, and communal uses without eroding local identity.

The project is structured around multiple, distinct programmatic layers. The core Agricultural Education Hub provides formal and informal learning environments focused on regenerative farming, climate adaptation, and land stewardship, integrating academic partnerships and residency-based research to facilitate regional knowledge transfer. Complementing this, specialised workshops and vocational training facilities engage unemployed or underemployed youth and adults, testing how targeted skill development linked directly to local environmental resources can mitigate outmigration and promote economic diversification. Cultural and community activities, including seasonal markets, cultural agricultural festivals, and local school programs, further structure social life, reinforce cultural identity, and create functional interfaces with visitors, evaluating

the potential of agricultural programming to support rural tourism without commodifying local traditions.

Architecturally, the proposal integrates visitor accommodation and innovative agro-village habitation prototypes directly into the landscape terrain. These elements combine walking trails, orchards, and historical routes into a cohesive, knowledge-based infrastructure that merges landscape, agricultural production, and everyday living. Strategically, the project measures the baseline effects of agricultural programming at the intersection of education, culture, and tourism, reframing rural life as an active, knowledge-based system and demonstrating how heritage, landscape, and productive activities can be reassembled into resilient infrastructures that support local livelihoods and broader sustainability goals. Together, these two complementary strategies demonstrate adaptive reuse as a multi-scalar framework linking architecture, landscape, heritage, agriculture, and socio-economic resilience in vulnerable rural contexts.

5 Results and Comparative Assessment

The design-led scenarios demonstrate different but complementary approaches to rural regeneration through adaptive reuse. Rather than functioning solely as architectural proposals, the scenarios operate as analytical tools evaluating how heritage assets, landscape systems, and socio-economic activities may be integrated to support environmental, social, and economic sustainability [8].

The Wellness, Nature, and Cultural Regeneration proposal primarily activates tourism, leisure, and cultural infrastructure through the adaptive reuse of the Verengaria Hotel and surrounding public spaces. The scenario suggests that wellness tourism and heritage-based recreation can strengthen economic diversification while reinforcing the symbolic identity of Prodromos village.

By contrast, the Agricultural Education and Cultural Centre proposal places greater emphasis on productive landscapes, agricultural knowledge exchange, and community participation. The scenario indicates that adaptive reuse linked to education and sustainable agriculture may support year-round activity, local employment opportunities, and stronger long-term demographic stability.

Both scenarios suggest that adaptive reuse can operate beyond the scale of individual buildings, functioning instead as a multi-scalar socio-spatial strategy connecting architecture, landscape, tourism, agriculture, and community life. The comparative analysis suggests that the two scenarios address different dimensions of rural sustainability. While the wellness and cultural strategy strengthens tourism visibility and heritage valorisation, the agricultural education model provides stronger integration between production, education, and local community resilience.

The findings indicate that adaptive reuse in rural settlements is most effective when implemented through interconnected systems rather than isolated building interventions. The integration of cultural heritage, productive landscapes, educational activities, and social infrastructure contributes to a broader understanding of adaptive reuse as a catalyst for regenerative rural development. A baseline programmatic comparison of these two distinct directional frameworks across key sustainability parameters is established in Table 3.

Table 3. Comparative Evaluation of Design Scenarios

Evaluation Criterion	Wellness and Cultural Hub	Agricultural Education and Cultural Centre
Heritage Preservation	High	High
Tourism Activation	High	Moderate
Community Participation	Moderate	High
Agricultural Integration	Low	High
Educational Capacity	Moderate	High
Environmental Integration	High	High
Year-Round Activity	Moderate	High
Economic Diversification	High	High
Potential for Population Retention	Moderate	High
Public Space Activation	High	Moderate

6 Discussion

The findings reinforce existing adaptive reuse literature highlighting the environmental and socio-cultural benefits of reusing buildings over demolition and reconstruction [1, 2]. However, this study extends the discussion by situating adaptive reuse within a rural, landscape-based context where architecture, agriculture, ecology, and community infrastructure are deeply interconnected. Unlike urban-focused reuse strategies centred on building preservation or commercial redevelopment, the Prodromos case shows that rural adaptive reuse must engage broader socio-spatial conditions such as depopulation, seasonal economies, agricultural decline, and reduced services. Here, reuse strengthens local identity, diversifies the economy, and enhances community resilience.

The research also demonstrates the value of design-led methods as exploratory tools in adaptive reuse studies, using speculative spatial scenarios to test how sustainability principles translate into spatial and programmatic strategies. Several limitations should be noted: the study is based on a couple of cases without quantitative environmental or economic assessment; the proposals are not implemented and therefore lack empirical validation; and the evaluation framework is qualitative rather than numerical. Future research could incorporate life-cycle assessment, embodied carbon analysis, stakeholder engagement, and feasibility studies alongside comparative cases across the Mediterranean to better understand context-specific conditions. Despite these limitations, the study highlights adaptive reuse as a promising rural regeneration strategy linking heritage, landscape, and productive activity within a wider sustainability framework.

7 Conclusion

Adaptive reuse offers significant potential to integrate environmental stewardship, cultural continuity, and socio-economic regeneration. Through the case study of Prodromos village and the Verengaria Hotel, this research has explored how adaptive reuse functions as a broader socio-spatial process connecting heritage preservation, tourism, agriculture, education, and community life. The study demonstrates that rural adaptive reuse requires approaches extending beyond architectural conservation alone. The design-led scenarios suggest that the integration of wellness tourism, cultural infrastructure, sustainable agriculture, and educational activities contributes to economic diversification, public space activation, and social resilience in depopulating mountain villages.

The application of the Adaptive Reuse Potential (ARP) model further supports the argument that heritage buildings possessing strong symbolic, environmental, and spatial value retain significant reuse capacity despite long-term abandonment and physical deterioration. Importantly, the findings indicate that adaptive reuse strategies are most effective when understood as interconnected systems linking buildings, landscapes, productive activities, and social infrastructures. Rather than presenting a universally transferable model, the research demonstrates how adaptive reuse can be investigated as an integrated socio-spatial process linking heritage conservation, environmental stewardship, tourism diversification, agricultural production, and community resilience in Mediterranean and similar peripheral regions.

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Circular Adaptive Reuse of Agricultural Industrial Heritage: Traditional Olive Oil Factories in Edremit Bay, Turkey

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Abstract. This study examines the potential for circular adaptive reuse of traditional olive oil factories in Edremit Bay as agricultural industrial heritage. Located on the Aegean coast of western Turkey, Edremit Bay is one of the country's leading olive-growing regions and has historically shaped local production landscapes and settlement patterns. The study aims to evaluate how these factories—many of which have become underused or abandoned—can be reintegrated into contemporary rural and cultural life through circular economy principles, beyond a solely fabric-oriented conservation approach. Methodologically, the study is based on a comparative multiple-case design involving six selected factory cases and combines (i) archival and literature research on regional olive oil production and industrial heritage, (ii) on-site observation and systematic documentation, and (iii) trace-grammar–based morphological analysis to decode spatial organization, material continuity, and heritage carriers that enable or constrain adaptive reuse. Findings show that the most suitable reuse pathways are not generic commercial conversions but low-impact hybrid scenarios combining cultural interpretation, public use, and carefully scaled agro-tourism. By comparatively testing reuse scenarios against circularity criteria—material retention, low-carbon upgrading, functional flexibility, and local value-chain reinforcement—the study proposes an evaluative framework tailored to agricultural industrial heritage. The study positions olive oil factories as strategic resources for regenerative rural development, circular design, and heritage regeneration.

Keywords: Agricultural Industrial Heritage · Olive Oil Factories · Circular Adaptive Reuse · Rural Regeneration · Edremit Bay

1 Introduction

The built environment lies at the center of contemporary sustainability debates because building construction, operation, demolition, and replacement are deeply entangled with material extraction, energy consumption, and waste generation. Within this context, circular economy thinking has increasingly been linked to adaptive reuse as a strategy capable of extending service life, conserving embodied resources, and reducing the environmental burdens associated with demolition-and-rebuild trajectories. Heritage buildings

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are not only material assets but also carriers of memory, identity, and place meaning. Their reuse combines environmental benefits with social, cultural, and territorial value [1–3].

Recent studies show that heritage reuse depends on architectural, structural, functional, environmental, legal, managerial, and socio-cultural factors, while circular heritage research increasingly calls for multicriteria decision-support tools [4, 6]. Yet this growing body of work still tends to privilege urban cultural heritage, landmark buildings, or industrial sites discussed in broad terms. Agricultural industrial heritage remains comparatively under-theorized, especially when examined as a circular adaptive reuse problem rather than solely as a conservation, tourism, or documentation issue. Existing studies on olive-oil mills, including those from Cyprus and western Anatolia, have demonstrated the heritage significance of these structures and their potential for new uses, but they have emphasized inventorying, typological reading, conservation principles, or heritage-route development rather than an explicit circular evaluation framework [4–8].

This gap is especially relevant in Edremit Bay, located on the Aegean coast of western Turkey, where olive cultivation has long shaped rural production landscapes, settlement patterns, and local economies. The broader Ayvalık–Edremit corridor emerged as a significant olive-based industrial territory during the late nineteenth and early twentieth centuries, and traditional olive oil factories became part of the region's architectural and socio-economic fabric. Today, many of these buildings are underused, abandoned, or transformed through interventions that overlook heritage values and long-term sustainability. Edremit Bay, therefore, offers a particularly strong case for investigating how circular adaptive reuse can be framed not only as building preservation but also as a strategy for rural regeneration grounded in local production history and cultural continuity [8, 9].

Against this background, this study asks: how can traditional olive oil factories in Edremit Bay be assessed as candidates for circular adaptive reuse in ways that retain heritage value while enabling low-carbon, locally embedded new uses? The study examines selected factories through archival research, on-site documentation, and trace-grammar–based morphological analysis, then evaluates reuse scenarios through four circularity criteria: material retention, low-carbon upgrading, functional flexibility, and local value-chain reinforcement. Recent circular heritage studies have underscored the need for operational criteria and participatory evaluation tools; building on that direction, this study proposes a transferable assessment approach tailored specifically to agricultural industrial heritage. In this sense, the paper's central contribution is not only to discuss the reuse potential of Edremit Bay's olive oil factories, but also to formulate an evaluative framework that can inform comparable rural agro-industrial heritage contexts [2, 6].

2 Materials and Method

This study employs a comparative multiple-case design to evaluate the circular adaptive reuse potential of traditional olive oil factories in Edremit Bay. The sampling frame was derived from a broader regional inventory of olive oil factories previously documented by the author [9]. Since the aim of the paper is not to produce a complete regional catalogue, but to test a transferable evaluative approach, six factories were selected through

purposive sampling. The selected cases represent abandonment, unfinished transformation, incompatible reuse, and comparatively compatible reuse (Table 1). Selection criteria were representativeness, transformation diversity, spatial-material legibility, and available documentary/on-site evidence. Table 1 summarizes the selected cases and their analytical roles.

Table 1. Selected cases and analytical role

Case	Condition	Analytical role
Ali Rıza Karagözoğlu	Abandoned	Vacancy/deterioration.
Sezai Ömer Madra 1	Abandoned	Legible unused fabric.
Terzioğlu	Unfinished	Interrupted transformation.
Sezai Ömer Madra 2	Incompatible reuse	Loss of industrial legibility.
Kırlangıç	Compatible reuse	Positive reuse benchmark.
Müderriszade Hilmi Efendi	Compatible reuse	Heritage–use continuity.

The empirical material consists of archival documents, secondary literature, field observation notes, and systematic building documentation. Archival and documentary sources reconstructed the regional context of olive oil production, previous transformation processes, and conservation status where available. On-site documentation combined photographic recording, field notes, and a comparable observation sheet covering physical condition, setting, structural system, material layers, production traces, later additions, circulation logic, and spatial fragmentation. This enabled the six factories to be assessed through the same observable indicators rather than descriptive case narratives alone.

The analytical core of the method is a trace-grammar–based morphological reading developed for this study. In this paper, trace-grammar is used as an operational reading tool that identifies how former production processes remain visible through spatial, material, structural, and symbolic traces. The analysis was conducted in three steps. First, observable traces were recorded for each factory through the field observation sheet. Second, these traces were grouped under four dimensions: spatial organization, material continuity, structural repetition, and heritage carriers. Third, the grouped traces were interpreted in relation to adaptive reuse potential. Spatial organization examined whether the former production sequence—entry, processing, storage, circulation, and service spaces—remained readable. Material continuity recorded the survival of stone, brick, timber, metal, lime-based finishes, and other fabric layers. Structural repetition evaluated the persistence of bay rhythm, roof span, load-bearing walls, trusses, and chimney-related spatial order. Heritage carriers identified the elements that most strongly communicate former industrial use, including machinery bases, pressing halls, chimneys, loading openings, courtyards, and attached storage volumes.

Based on this morphological reading, four circularity criteria were selected by translating broader circular economy principles into indicators applicable to agricultural industrial heritage. The criteria were also chosen because they correspond to the main

reuse challenges observed in the selected factories: retaining original fabric, improving performance without heavy reconstruction, accommodating new functions, and reconnecting buildings to local olive-based economies. Material retention refers to the extent to which original building fabric and surviving industrial components can remain in use rather than be removed or replaced. Low-carbon upgrading evaluates whether comfort, safety, and technical performance can be improved through repair, reversible additions, and limited material substitution rather than energy-intensive reconstruction. Functional flexibility assesses whether the spatial and structural configuration can accommodate new programs without severely disrupting the inherited building logic. Local value-chain reinforcement considers whether proposed new uses can reconnect the factory to local olive culture, crafts, agro-tourism, education, or community-based economic activity. Four reuse scenarios were then comparatively tested—interpretive production museum, small-scale cultural hub, agro-tourism facility, and mixed community venue—using a compact ordinal matrix of high, medium, and low suitability (Table 2).

Suitability levels were assigned qualitatively according to the degree of compatibility between each reuse scenario and the morphological evidence recorded in the six cases. A "High" value indicates that the scenario can be accommodated with limited intervention while retaining key heritage carriers. A "Medium" value indicates that the scenario is possible but requires careful design control to avoid loss of legibility or excessive technical insertion. A "Low" value would indicate a strong mismatch between the proposed function and the inherited spatial-material logic. No scenario was assessed as uniformly low because all four options were selected as potentially plausible reuse pathways; the matrix therefore functions as a comparative screening tool rather than as a final design prescription.

Table 2. Comparative suitability of reuse scenarios according to circularity criteria

Reuse scenario	Material retention	Low-carbon upgrading	Functional flexibility	Local value-chain reinforcement
Interpretive production museum	High	High	Medium	Medium
Small-scale cultural hub	High	High	High	Medium
Agro-tourism facility	Medium	Medium	Medium	High
Mixed community venue	Medium	Medium	High	Medium

3 Edremit Bay Olive Oil Factories: Morphology, Heritage Values and Reuse Potential

Edremit Bay is a layered agro-industrial landscape where olive cultivation, processing, storage, and trade shaped settlement structure and everyday life. In this context, olive oil factories are production-linked heritage assets embedded in streets, village edges, courtyards, and grove-based rural routes. The selected cases represent different transformation conditions, enabling comparison of reuse potential across varying degrees of preservation, intervention, and functional continuity.

The findings were derived by comparing the six cases across the same morphological dimensions and circularity criteria. Abandoned, unfinished, incompatible, and compatible reuse cases revealed recurring patterns of heritage legibility, intervention risk, and functional fit rather than isolated case-specific observations.

Across the selected cases, the most consistent typological features are compact but high-volume masonry shells, repetitive structural bays, robust load-bearing systems, and production-related appendages such as chimneys, courtyards, storage spaces, and loading openings. These characteristics are important because they allow new functions to be inserted without necessarily replacing the inherited spatial order. The abandoned cases demonstrate that even unused factories may retain strong reuse potential when halls, chimneys, and loading thresholds remain readable. Conversely, the inappropriately converted case shows that reuse alone does not guarantee heritage continuity when interior subdivision, façade alteration, or excessive service insertion weakens the original production logic. This finding supports adaptive reuse research showing that intervention intensity increases when the mismatch between inherited building configuration and new function becomes too large [10].

The trace-grammar–based morphological analysis indicates that the most enabling features for adaptive reuse are the readability of the original production sequence, the persistence of repetitive structural rhythm, the continuity of masonry fabric, and the survival of strong heritage carriers such as chimneys, pressing halls, machinery bases, and loading thresholds. These elements support reuse because they make the building intelligible without requiring excessive reinterpretation; they also allow new uses to be inserted while keeping the industrial narrative visible. By contrast, reuse potential becomes more limited when roof collapse disrupts volumetric continuity, when façade openings are blocked, when reinforced-concrete additions disturb the original load-bearing logic, or when interior subdivisions erase the legibility of production space. This finding aligns with broader adaptive reuse literature showing that intervention intensity rises when the mismatch between inherited spatial structure and proposed new function becomes too large, and that industrial heritage projects perform better when new uses work with, rather than against, the building's structural and morphological grain [2, 10].

Within this framework, the primary heritage carriers that require retention are not limited to monumental exterior elements. Equally important are the internal spatial order, material patina, traces of production equipment, wall thickness, roof geometry, and the building's relation to its immediate setting. In circular terms, these carriers matter because they concentrate both embodied material value and interpretive value. Their retention increases material continuity while also strengthening the distinctiveness that

can support locally grounded new uses. Accordingly, four reuse scenarios were comparatively tested through the circularity matrix presented in Table 2: interpretive production museum, small-scale cultural hub, agro-tourism facility, and mixed community venue. The museum scenario performs strongest in material retention and heritage legibility, since it can preserve machinery traces, chimney symbolism, and the original processional reading of space with minimal subdivision. The cultural-hub scenario offers the best balance between retention and functional flexibility, especially in factories with large, undivided halls that can host exhibitions, workshops, and seasonal events without major structural change. Agro-tourism performs strongly in local value-chain reinforcement by reconnecting buildings to olive culture, gastronomy, and rural visitation. However, it requires tighter control to avoid excessive compartmentalization or hospitality-driven insertions. Mixed community use scores highest in flexibility, yet it risks becoming too generic when the industrial narrative is not actively curated. The comparative logic here follows circular adaptive reuse thinking that privileges compatibility among the existing fabric, the future program, and the intervention level over one-size-fits-all functional replication.

The strongest result of the analysis is that the most suitable futures for this building type are hybrid scenarios centered on cultural interpretation + low-intensity public use, rather than purely commercial conversions copied from one case to another. Factories with readable halls, surviving chimneys, and robust masonry envelopes are particularly well suited to combinations of interpretive museum, cultural venue, and carefully scaled agro-tourism. These uses align with the buildings' spatial generosity and industrial identity while keeping material replacement and structural intervention low. By contrast, generic-market, café-, or hotel-led conversions become more problematic when they require mezzanines, dense service cores, façade alterations, or the removal of industrial traces. What distinguishes the Edremit Bay cases, therefore, is not simply that they can be reused, but that their most circular futures depend on matching new functions to inherited morphological logic. The proposed assessment approach therefore adds value by identifying which spatial and material characteristics make certain reuse scenarios more compatible, and therefore more sustainable, than others.

4 Discussion

This study shows that circular adaptive reuse is most convincing when the new program works with the building's inherited morphological logic rather than against it. In the Edremit Bay cases, reuse potential increased where production halls remained legible, structural bays were still readable, masonry continuity was preserved, and industrial carriers such as chimneys, loading thresholds, and machinery traces survived. This result is consistent with circular adaptive reuse research, arguing that environmental gains are maximized when interventions prioritize retention, reduce demolition, and minimize the material intensity of upgrading. It also aligns with systematic review evidence showing that successful heritage reuse depends not on a single design gesture, but on the interaction of architectural, structural, functional, environmental, socio-cultural, legal, and management factors. In that sense, the Edremit analysis supports the growing literature calling for explicit, ex ante, multi-criteria assessment tools rather than ad hoc conversion decisions.

The importance of this contribution lies in its focus on rural agricultural industrial heritage. This category remains underrepresented in circularity debates compared with large urban industrial icons or metropolitan heritage districts. A review of 190 European circular city plans found that only 7% explicitly included cultural heritage, suggesting that, even where circularity has entered policy discourse, heritage reuse remains far from central. At the same time, studies on olive-oil mills in Cyprus and Ayvalık have clearly demonstrated the heritage significance and reuse potential of these buildings. Yet, they have mostly framed the issue in terms of conservation value, documentation, or tourism-related reuse rather than a circular evaluation framework. The Edremit Bay cases, therefore, help shift the discussion from whether olive oil factories should be conserved to how their spatial and material characteristics can be systematically matched with low-impact future uses. Because similar olive-based production landscapes exist across western Türkiye and the eastern Mediterranean, this framework is transferable. However, its application would still need to be adjusted to local policy settings, ownership structures, and market conditions.

From a circular economy perspective, the value of these factories lies not only in heritage continuity but also in the conservation of embodied materials, the avoidance of demolition waste, and the possibility of low-carbon upgrading through repair, reversible additions, and limited replacement. The practical implication is that reuse decisions should begin with a morphological compatibility check before a new function is selected. For municipalities, this means that abandoned olive oil factories can be incorporated into rural regeneration strategies as cultural, educational, and agro-tourism assets rather than treated only as isolated restoration objects. For conservation boards, the findings suggest that chimneys, processing halls, machinery traces, loading thresholds, material patina, and spatial sequence should be protected as primary heritage carriers. For property owners and rural development actors, the results indicate that low-intensity hybrid uses are more suitable than generic commercial conversions when the aim is to retain heritage legibility and reduce intervention intensity. Therefore, the main practical lesson is clear: the stronger the fit between inherited building logic and future program, the more circular, legible, and territorially embedded the reuse pathway becomes.

5 Conclusion

This study answers the research question by showing that traditional olive oil factories in Edremit Bay can be strong candidates for circular adaptive reuse when future functions align with the inherited spatial logic, material continuity, and the surviving carriers of industrial identity. The analysis demonstrates that the most suitable reuse pathways are not generic commercial conversions, but low-impact hybrid scenarios that combine cultural interpretation, public use, and carefully scaled agro-tourism. Such scenarios offer the strongest balance between material retention, low-carbon upgrading, functional flexibility, and local value-chain reinforcement, while maintaining the architectural and territorial legibility of the factories.

The study makes three main contributions. Conceptually, it extends circular adaptive reuse debates from urban industrial landmarks to the underexplored field of rural agricultural industrial heritage. Methodologically, it proposes a concise assessment approach

that combines trace-grammar–based morphological reading with four operational circularity criteria. In practical and policy terms, it offers a preliminary decision-support tool for municipalities, conservation boards, property owners, and rural development actors. Since the assessment is qualitative and ex ante, it should be complemented in future studies by detailed structural surveys, cost analysis, user studies, and environmental performance calculations. Nevertheless, the Edremit Bay cases indicate that agricultural industrial heritage can serve as an active resource for regenerative rural development and a broader circular heritage transition when future functions are matched with inherited building logic.

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The Fate of Buildings: Adaptation or Demolition? Comparative Insights from the UK and Australia

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Abstract. The built environment plays a significant role in achieving global decarbonization. Nevertheless, the decision to adapt/demolish existing buildings is often based on uncoordinated and incomplete criteria with limited focus on circularity and varying views of obsolescence. This paper explores how building adaptation decisions are influenced by different factors and contextual pressures. It draws on a documentary analysis between Sydney and London identifying evidence during building redevelopment processes. The findings suggest that adaptive reuse is possible when structural feasibility, market repositioning and sustainability goals align among the involved actors in a decision-making process. This comparison suggests that obsolescence is a matter of negotiation rather than a fixed state, emphasizing the need for a clearer and systematic decision support to incorporate social and technical dynamics and facilitate a transition towards a circular built environment.

Keywords: Adaptive Reuse · Building Demolition · Decision making

1 Introduction

Climate change (CC) is drawing attention to the environmental burdens of built environment practices. This prompted Circular Economy (CE) strategies that shift attention from the linear model of buildings towards retaining, adapting, and repurposing existing buildings [1]. Across Europe, the building stock is ageing with a large share failing to meet current energy performance standards. Around 85% of the buildings are energy inefficient and progress towards a target 3% renovation rate remains slow. The UK faces a similar challenge, with 80% of existing buildings expected to remain in use by 2050, while fewer than 1/3 currently meet the energy efficiency requirements [2]. Policy is focused on improving performance through deep retrofit strategies yet many buildings cannot easily accommodate the functional and technological upgrades required today [3]. This leaves them vulnerable to premature or unnecessary demolition as user needs and regulatory demands evolve [4]. Several studies agree that the adaptation of buildings can be a value driver and may help reduce unnecessary demolitions [5]. However decisions to adapt or demolish buildings are inherently complex and rely on a mixed

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criterion [6]. Understanding how social and technical factors interact during the decision process and their role in promoting circularity of buildings remains limited. This paper contributes to the literature by asking: What factors affect the decision of building adaptation or demolition?

2 Literature Review

2.1 Building Adaptation

Building adaptation is defined as "any work performed on a building over and above maintenance to change its capacity, function or performance". A growing body of literature links adaptability with circularity, arguing that reuse oriented design strategies preserve embodied carbon, extend service life and reduce unnecessary demolition by enabling buildings to evolve with user and regulatory needs [5, 7]. Despite its potential, there remains inherent complexity in the decision-making process of choosing whether to demolish or adapt a building [6]. Successful adaptive reuse requires stakeholders to balance a wide array of interrelated factors including architectural, physical, economic, sociocultural, environmental and legal dimensions [8]. To navigate this multidimensional challenge, much of the research focuses on developing robust decision-support tools, multicriteria decision making [9], mathematical algorithms and weighted checklists [10], SWOT analysis [9], and financial performance studies [11]. Despite the potential of such innovations, several critical gaps remain. One gap relates to the implementation blind spot where preconstruction and design phases are heavily researched while the actual implementation process is largely overlooked. Another is the apparent disconnect between the theoretical frameworks and empirical validity, and effectiveness in real world localized contexts [12] making it a key challenge for adaptive reuse research.

2.2 Data and Information

Information and data management is a critical yet challenging aspect of building adaptation and circularity [12]. Many existing buildings lack accurate documentation, incomplete records [9] compounded by information asymmetry and fragmented communication among project actors [13]. Researchers note a lack of timely information sharing between project phases such as the hand-off between design and construction; this creates information silos can significantly increase decision-making complexity, project risk, and hidden transaction costs [12]. The data challenge also applies to the challenge of requiring whole life embodied carbon data before any demolition decision [14], which can be difficult due to methodological inconsistencies, lack of localised LCA databases and using international or unreliable manufacturer data [3]. In addition, carbon assessments incorporate dynamic factors such as grid decarbonisation which can lead to incorrect payback times and whole life impacts. These uncertainties place greater importance on trust as a crucial mechanism for effective project coordination and information exchange to address these issues [2] emphasising the need for transparent shared digital records that improve reliability.

2.3 Stakeholders' Roles

Adaptive reuse acts as a complex sociotechnical transition accompanied with organizational and interdisciplinary tensions involving various actors including investors, developers, regulators, designers, and users, who frequently hold conflicting interests and beliefs [15, 16]. For that transitioning to circular practices often challenges established hierarchies; role changes for instance can provoke political conflicts and defensive behaviours [13]. For agreements to be reached, a sequence of principled negotiation and compromises may work better than an expectation of consensus [15]. Prioritising one demand over the other, for example chasing financial returns versus ensuring historic preservation, often triggers unintended negative consequences. To manage conflicting demands, a paradox perspective is suggested, seeking "both/and" solutions to integrate conflicting needs rather than "either/or" compromises that optimise one side while abandoning the other. Collaborative rationality and active stakeholder engagement [1, 15] may resolve such challenges, several approaches were introduced including participatory scenario-building [17], collaborative frameworks [18] and policy instruments to help surface these organizational tensions, allowing diverse actors to navigate complexity and collaborate to reach collective decisions [7]. Despite their potential, it is still needed to better manage interactions during decision making and help the building stock meet its climate and decarbonisation targets [15] they remain largely focused on front-runners, overlooking the resistant actors [13].

3 Methods

3.1 Research Design

A documentary analysis was conducted to compare two cases of urban non-residential buildings facing demolition or adaptation: Orchard House (London) and the Quay Quarter Building (Sydney). Documentary research enables the systematic collection and interpretation of texts to identify features of events or cases to develop credible evidence-based interpretations and allows the findings to be connected to broader policy and industry practices [19]. The analysis drew on publicly available materials which were selected based on their direct focus on the adapt/demolish decision of the selected cases and their submission by a professional affiliated body. Documents whose reference to the site was incidental or purely promotional were excluded. The results are in (Table 1) below. Each document was examined through a structured analytical matrix starting with document authorship including any professional affiliations or institutional positions that may have shaped the perspective conveyed. Second, the purpose and motivation underlying each document was examined to understand the drivers such as social, political, economic, or historical factors informing its creation. Additionally, the intended audience was identified, helping to reveal whether the documents responded or sought to advance a particular agenda. The analysis further considered the documents' positioning and content, including connections to other sources as well as omissions or silences that might indicate deliberate gaps or biases. Finally, comparative sources were reviewed to support triangulation and each document's reliability, and credibility was assessed to determine its overall evidential value within the study.

Table 1. List of sources for the documentary analysis

#	Type	Description
D1	Planning report	Proof of Evidence and planning application 21/04502/FUL
D2 D3	Design Report	458 Oxford Street Project - Pilbrow and Partners Greater London Authority (GLA): Stage 2 Addendum Report for M&S Oxford Street
D4	Decision letter	Decision letter 456–472 Oxford street, London
D5	Case Summary	Town Legal LLP: Save Britain's Heritage v Secretary of State (2018)
D6	News Articles	Multiple Media Articles
F1	Planning report	Quay Quarter Building Construction management plan
F2	Design Report	ACAA Technical Paper: Quay Quarter Building Construction and Structural Design
F3	Case Summary	UKGBC Case Study Library - Quay Quarter Building
F4	News Article	Schindler Group: Quay Quarter Building – A building reimagined

4 Discussion

4.1 Project 1: Orchard House Building

Orchard House is a prominent 1930s commercial building located on London's Oxford Street. It is owned by a retail developer and is not listed as a heritage building despite its significant history in London. Redevelopment debates started in 2021 when the developer submitted a planning application for demolition of 3 existing buildings and construction of a new mixed-use building as shown in Fig. 1.



Fig. 1. The Orchard House Existing State vs. the expected development scheme (Images: D2)

From 2021 to 2024, significant tensions arose between stakeholders pushing for urban economic recovery, and those emphasising climate and conservation concerns. For the first group, although adaptive reuse was examined, designers and architects stated that the arrangement of the buildings, including Orchard House, prevented any deep- retrofit scheme from being structurally feasible. Instead, they proposed a new build scheme that claimed an outstanding environmental certification rating, a longer design

life, reduction in operational energy, short (embodied) carbon payback and promised creation of several jobs. Within the second group were various organizations supporting retention and retrofit, who argued that the demolition would release an immediate and catastrophic amount of embodied carbon, and would lead to the loss of important heritage. This debate was further complicated by the UK planning and government systems. Westminster City Council and Greater London Authority initially gave outline approval for demolition to ensure Oxford Street's economic recovery, but objections on climate and heritage grounds led to demolition being refused. The justification for refusal referred to the National Planning Policy Framework (NPFF) that states "some encouragement for the reuse of buildings". The retail developer appealed this decision, with the argument that retaining the building posed a threat to the urban development of the street where vacancy rates were already high and existing buildings were no longer suitable for contemporary retail requirements. The appeal was heard in the High Court, where judicial review determined the decision against demolition had been unlawful and that the NPPF had been misinterpreted as indicating a strong presumption against demolition. Furthermore, the court highlighted that there is a systemic struggle to accurately measure embodied carbon data, noting that a crucial error had been made of applying carbon offsetting requirements to embodied carbon when legally the policy only applies to operational carbon. Ultimately, the decision to demolish was approved, suggesting that in the absence of hard legally binding embodied carbon limits, or policies that mandate retrofit, demolition will be the default decision irrespective of environmental and cultural damage.

4.2 Project 2: Quay Quarter Building

The second building, Quay Quarter Building, is a prominent commercial building located in Sydney's Circular Quay (Fig. 2). When it was completed in 1976, the building was the tallest in the city, but by 2014 was nearing the end of its commercial life.



Fig. 2. Before and After Development of Quay Quarter Building (Images: F2)

The ageing building suffered from relatively small floor plates that no longer appealed to prospective tenants, resulting in diminishing returns. The established option therefore was to demolish, although it was acknowledged this would generate massive waste, and rebuild to an optimised specification, which would emit significant additional embodied carbon. While a standard retrofit would prolong the building's life, it was deemed commercially unviable as it would fall short of the prime site's potential. In addition, this approach was severely complicated by systemic and structural challenges. Nevertheless,

this was the solution chosen. Upgrading a 1970s concrete structure to meet contemporary construction standards required extensive strengthening. Technical conflicts arose around the integrating the old, fully settled concrete core with a massive new structure, requiring the team to account for a variety of structural deformations in the floor plate. To maintain economic viability and speed, a complex construction sequence was used allowing for a top-down demolition of 1/3 of the existing building concurrently with the bottom-up construction of a new composite structure at the ground level of the building. Ultimately the upcycling of the Quay Quarter building was hailed as an overwhelming triumph of adaptive reuse and a demonstration of how adaptive reuse and commercial expansion can coexist. This project saved significant amounts of embodied carbon.

4.3 Comparative Analysis of Project 1 and Project 2

Despite presenting similar forms of obsolescence, Orchard House (Project 1) and the Quay Quarter Building (Project 2) were interpreted differently, leading one toward retention and the other toward demolition. In Project 2, early feasibility studies showed that the existing structural cores could be reused, and this evidence aligned with developer ambitions, carbon-efficiency goals and a market strategy centred on repositioning the building. These conditions created a shared narrative that framed obsolescence as a challenge that could be resolved through innovative adaptation. In project 1, however, obsolescence was framed primarily through a commercial redevelopment narrative. The developer and architects argued that the fragmented configuration of the three buildings limited retrofit feasibility; although other designers disagreed and offered alternative viable designs, the first interpretation aligned with incentives to deliver a new high-performance retail scheme. The decision process became highly politicised, with conflicting expert views, NGO pressure, and inconsistent policy interpretations contributing to a fragmented environment in which the technical case for retention struggled to gain traction. These contrasting outcomes suggest that the difference between the two cases does not lie only in technical assessments, but also in how actors interpret and negotiate those assessments within their specific political, economic, and organisational contexts. While policy structures have a broader aim of supporting climate efficient construction practices, they conversely played a role in facilitating the justification for demolition in this case. At Quay Quarter Building, adaptive reuse potential was fully realised, supported by minimal resistance from involved actors, strong design leadership, aligned developer priorities, and clear technical evidence. In contrast, Orchard House failed to capture any adaptive reuse value despite resistance from several actors. Conflicting interpretations of design, carbon evidence, and inconsistencies in planning policy created barriers that favoured demolition, showing how two cases with similar conditions can produce different interpretations and decisions. However, it is important to note that decision making involves navigating both formal and informal complex interactions among stakeholders, which may not be reflected in the documents highlighting a limitation of this research and demands a further in-depth study.

5 Conclusion

This paper examines how decisions to adapt or demolish existing buildings are formed in practice, highlighting the social, technical and contextual influences shaping adaptation processes. A documentary analysis of two projects showed these decisions extending beyond technical assessments or environmental considerations. Instead, they emerged through negotiations involving structural feasibility, stakeholder interests, policy interpretation, market pressures and the narratives decision makers used to justify outcomes. Despite increasing policy attention on embodied carbon and circularity, these considerations often remain marginalised within real decision processes. The next stage of this research will explore how actors construct obsolescence, mobilise evidence, and negotiate competing values in real decision environments. This will help strengthen decision making process to better integrate circularity.

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From Barriers to Solutions: Lessons Learned from Community Based Urban Mining in Belgium

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Abstract. Urban mining focuses on reclaiming and reusing construction materials from buildings slated for intensive renovation or demolition, and is increasingly recognized as a strategy for achieving circular construction practices. As an emerging research field, urban mining faces significant barriers including a lack of public awareness and negative social perceptions. This research therefore investigates the role of community involvement in overcoming challenges across urban mining project phases. This paper presents three Flemish urban mining case studies featuring the community: the Albert building transformation for disaster relief, the RTT/De Pastorie by Hasselt University, and the Blikfabriek. The cases demonstrate that while each project is context-specific, urban mining challenges surrounding limited time, labor, and material reuse applications can be mitigated through community involvement. In the Albert building, volunteers worked together to overcome time and labor constraints and provide mutual aid. In the RTT/De Pastorie case, discussions with the community informed decision-making, shedding light on the neglected emotional aspect of urban mining and the value of local knowledge. Lastly, the Blikfabriek serves as a case of contemporary material culture, connecting the local community to the potentials of reused materials. Based on these insights, the paper presents recommendations for community involvement in urban mining projects as a means to enhance their feasibility, social acceptance, and alignment with circular economy principles.

Keywords: Urban Mining · Circular Economy · Community Involvement

1 Introduction

Despite the developments towards a Circular Economy (CE), researchers argue that the current measures for implementing circularity in buildings fall short, and that the focus must evolve from less circular practices like recycling to more circular practices such

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as reuse. This means a shift away from building demolition and new construction, and towards maintenance, renovation, and deconstruction [1]. Through reclaiming anthropogenic stocks from urban areas, primarily for reuse [2], Urban Mining (UM) emerges as a promising solution to replacing current construction and demolition cycles with circular construction. Literature defines three main phases for such projects: identifying, harvesting, and distributing reusable building elements [3]. Identifying involves selecting a building and determining what could be harvested. Harvesting involves dismantling, cleaning, and preparation of materials for reuse. Lastly, recirculation concerns how harvested materials are integrated into new projects. As each building and UM process is context-specific, projects face diverse logistical, financial, and societal barriers throughout project phases [4]. Local communities hold a critical position in mitigating such barriers and enabling mutually beneficial circular construction practices and UM processes. The direct reuse of building elements in particular contributes to environmental sustainability and social cohesion which benefit the local community. In return, the community may facilitate direct reuse through active participation, leading to positive social awareness and perception [4]. However, research on the societal dimension of UM is notably limited. Presenting and analyzing three case studies, this paper therefore establishes an essential discourse surrounding the potential for community-based solutions to UM barriers. The paper adopts the three-phase UM framework of identifying, harvesting, and recirculation as an analytical lens for examining how community involvement can act as a socio-technical mechanism influencing knowledge exchange, stakeholder engagement, societal dynamics, and material recirculation pathways. Across the three case studies, the analysis covers barriers encountered in each UM phase, forms of community involvement, and the resulting effects on project feasibility, social acceptance, and reuse implementation. In this way, the paper investigates the research question: How can community involvement support UM practices across project phases?

2 Materials and Methods

Responding to the low number of documented UM cases, this paper adopts an exploratory, qualitative case study approach. The three selected cases are not presented as best-practice examples, but rather as context-specific projects that reveal how community involvement may support UM processes under real-world conditions. While data collection methods varied slightly across cases according to project accessibility and available documentation, each case was examined through the same analytical structure based on the three UM phases: identifying, harvesting, and recirculation. Primary data collection consisted of semi-structured interviews with project actors, complemented by project documentation, publicly available publications, guided site visits, and visual material. Interview notes and project documentation were analyzed thematically according to the three UM phases. Recurring barriers, forms of community involvement, and reuse applications were identified across the three cases and comparatively interpreted. In the presentation of each case, the context is first established, then the role of the local community and the barriers that were addressed are explored for each UM phase. Section 3 explores the community-based UM project organized by Evy Puelinckx for disaster relief, highlighting the humanitarian dimension of community-based UM. It

consults openly available resources, namely news and thesis publications featuring interviews with Puelinckx. Section 4 tells the story of inter-building, socially aware UM for urban regeneration as managed by UHasselt. The narrative constructed in this paper is the result of interviews between the authors and project coordinators Peggy Winkels and Irina Prooth of UHasselt in May 2025. In Sect. 5, an ad hoc, community-based approach to UM with defined socio-cultural value is presented through the Blikfabriek. This section is based on the author's on-site interview and guided tour with project manager Joris Goorden in March 2026. Section 6 presents reflections on the cases as community-based solutions for UM projects. The role of community members in each project phase are presented alongside the UM barriers they addressed to highlight the diverse roles community involvement can play in UM to enhance their feasibility, social acceptance, and alignment with CE principles.

3 Case: Albert Building Transformation for Disaster Relief

In 2021, Wallonia was struck by floods, causing damage to numerous homes. To provide timely aid to the flood victims, UM specialist Evy Puelinckx recognized the need for a community-based approach to UM, calling on volunteers to help harvest and distribute interior components [5].

Due to her background in architecture and UM, Puelinckx was easily able to identify the UM potential of the Albert building, an office building which was to be transformed into an apartment complex [6]. Before the project's official start, direct collaboration with the building owners was established based on the company's own dedication to sustainability and belief in the humanitarian benefits of the project. Although the owners had limited prior experience with UM, by leveraging community involvement and her own expertise, Puelinckx successfully reasoned for the UM project to be executed. Less straightforward was the task of identifying what could be successfully removed, specifically by volunteers who lack dismantling experience. This challenge was mitigated by discussions leading to personal profiles to help distribute responsibilities based on the capabilities of the volunteers [5]. Through this collective effort, volunteers were able to systemically identify which components they could successfully harvest, addressing a common uncertainty in gauging opportunities for UM.

Empowered by numbers, the volunteers were able to make efficient use of their various skill levels during the harvesting phase to reclaim valuable building components that would have otherwise been discarded. In the end, the group was able to harvest a total of 50 toilets, 10 kitchen sets, shower appliances, and more [6]. This large quantity of harvested components represents the advantage of collective action in producing effective results outside of mainstream construction and demolition cycles without incurring additional costs. In this way, community involvement allowed the project to overcome a major structural barrier to UM: circularity principles are often forgotten as projects prioritize time and financial efficiency.

The recirculation phase moved the project beyond extraction, symbolizing the potential of UM in collective action and mutual aid. The transportation of the harvested materials was managed by the original building owners, and their distribution within the affected communities was organized by local volunteers [6]. This community involvement, paired with the community-based application, allowed the project to overcome

the bottleneck of the fragmented network hindering UM practices. Puelinckx notes that UM projects benefit from defining reuse applications early on to ensure value retention of the harvested components [5]. In the case of the Albert building, the reuse application was straightforward as communities were aligned in giving and receiving the harvested components. This helped materials avoid being sent to storage for undefined periods of time and instead enabled efficient reuse.

4 Case: The RTT to De Pastorie by Hasselt University

In 2024, an infrastructural plan which required the removal of several buildings, including private homes around the Noord-Zuid Limburg (NZL) road transition project was introduced. Given the exceptional condition of the buildings and the emotional uncertainty among residents, the UM project team explored whether demolition could shift from a rapid clearance process to an opportunity for urban renewal.

Conversations with residents surfaced emotional discomfort regarding extraction from personal homes, and commercial and public buildings were identified as the more suitable opportunities for harvesting. Additionally, discussions by the NZL Consortium and student surveys led to the identification of the former RTT telecommunications building as an urban mine due to its scale and quantity of reusable materials. The RTT was then designated as a donor building for the renovation of de Pastorie, a former rectory also embedded in the NZL project. Identifying which buildings and materials could be harvested highlighted a key tension: initial assessments emphasized economic or technical value, ignoring social and emotional dimensions. While this phase revealed narrow valuation frameworks as an UM barrier, it also showed that early engagement with community members can remediate such constraints as local actors contributed insights that institutional partners alone could not provide.

Rather than operating as a technical extraction operation, harvesting then unfolded as a collaborative, situated practice rooted in the established relationships. Although selective dismantling proved labor intensive (removing a single tile took roughly 10 min), community participation reframed harvesting from an efficiency-driven task to an experimental, collective act of care and stewardship. Researchers and students worked alongside locals, promoting practices of documentation and reflection that temporarily disrupted conventional demolition logic. The Friends of De Pastorie, a local citizen initiative, helped mobilize additional volunteers for collective harvesting days, progressively improving efficiency. Active participation from community members embedded educational, social, and emotional value within the harvesting process, demonstrating that community involvement may not eliminate structural barriers, but can form pathways for navigating them [7].

The next step was to reintegrate harvested materials into a shared spatial experiment, de Pastorie. Locally, however, reused materials were still not immediately perceived as valuable. Many residents associated older materials with waste, and architects initially hesitated to incorporate the harvested materials, citing concerns about consistency, aesthetics, and long-term durability. Reuse then became part of an ongoing dialogue between designers, researchers, and residents. Participatory design processes were adopted to meaningfully integrated harvested materials in de Pastorie. The narrative dimension proved crucial as materials surpassed their conventional roles to embody

the collective memory and effort of the transformation, reinforcing the sociocultural value of circularity [7]. Volunteers could point to the tiles and say, "we harvested this ourselves," fostering collective pride and ownership. By making material circulation visible and traceable, the project strengthened the social legitimacy of localized reuse and challenged cultural barriers surrounding the value of reclaimed materials.

5 Case: The City to the Blikfabriek

Located in a working-class neighborhood in Antwerp featuring residences, small businesses, urban facilities, and increasingly abandoned industrial sites, the area surrounding the Blikfabriek (tin can factory) faces social and spatial fragmentation. In 2013, the original Blikfabriek shut down and, starting in 2018, the site has been transformed through an incremental, participatory approach by a community of caretakers and users supported by social, creative, and cultural networks.

From the project's beginning, the space has developed incrementally, the large site naturally growing as a host space for materials looking for a second life; materials from temporary installations, renovations, and demolition projects across the city. In this way, the initial development team, including an artist collective and cultural curator, based the site's transformation on freely availability of resources. Rather than generating demand for new materials, they respond to available resources from factories, museums, film sets, the opera, and so on. Through social and professional connections, the Blikfabriek has become the destination for material reuse, effectively operating as a node within a decentralized, informal network of UM practices. This network operates without relying on formal governance structures, instead leveraging relationships and shared values for community-based resource identification and harvesting.

This case does not conform to the typical identify-harvest-recirculate project phasing. Such an unconventional approach to urban regeneration through UM has transposed the traditional role of developers and project managers into a community of caretakers. Operating as custodians of the site's social and spatial ephemerality, they curate and maintain the space as it shapes, and is shaped by, the comings and goings of the larger community. This ad hoc ecosystem has enabled the Blikfabriek to practice UM in a way that forgoes conventional donor and recipient dynamics, instead developing organically and in tandem with its community. Although this open-ended approach requires significant time, flexibility, and continuous stewardship, it has nonetheless helped to circumvent systemic barriers such as limited resource availability, rigid assessment frameworks, and financial and administrative burdens associated with formal harvesting operations.

Through the project's city-scale approach to identification and harvesting, countless instances of reuse have occurred. Timber beams from an old hangar in the Antwerp harbor became a pergola for outdoor seating, soil from local construction sites was used for on-site landscaping, and oversized artworks from local creators breathe in new life throughout the site. The Blikfabriek's success can be attributed to the situated, involved nature of its organizational model and organic approach to UM. It reframes urban renewal from a top-down redevelopment process to an evolving, collective practice rooted in do-it-yourself ethos and local creative capacity. Through incremental building, improvisation, ongoing participatory processes, and mutual support, the site demonstrates how

community-driven UM can produce a socially vibrant environment while showcasing the transformative potential of reclaimed materials.

6 Discussion

Across the three cases, each case operated under distinct conditions in which community involvement emerges as a driver for enhancing the feasibility, social acceptance, and circular potential of UM practices. Through their diverse contexts, they demonstrate how early engagement, capacity building through participation, and visible material narratives establish socially embedded, context-responsive practices to strengthen UM outcomes. Table 1 comparatively synthesizes how the community involvement contributed to overcoming barriers across the different UM phases in each case.

Proactive dialogue during the identification phase among stakeholders clarified what was both materially possible and socially acceptable, mitigating barriers including limited organizational structures and narrow valuation frameworks. In the Albert building, task allocation through volunteer skill profiles matched dismantling complexity to capabilities, ensuring safe, effective harvesting by nonprofessionals. In the RTT/De Pastorie, early dialogues with residents revealed emotional sensitivities around extracting materials from private homes, informing decision-making to harvest non-residential buildings. In the Blikfabriek, trust evolved from long-standing relationships between artists and local organizations, allowing the site to operate as a material reuse node within a circular system. Across the three cases, early alignment introduced clarity and nuance, anchoring decisions in shared values.

Throughout harvesting processes, building UM capacity through community involvement addressed practical constraints to UM while building local competences, embedding educational and social values, and broadening stewardship. Through concerted volunteer efforts in the Albert building, local community members were able to gain hands-on experience and harvest high volumes of reusable components, building local capacity and adding value to the conventional renovation processes. Guided tours, plain language informational material, and volunteer days in provided low-threshold entry points for local communities and demystified UM in de Pastorie. Providing an accessible and interactive approach to UM allowed the harvesting phase to balance care and stewardship with efficiency, improving the local community's connection to the developing urban fabric without significantly delaying the larger infrastructural works. Open workshops, visible reuse culture, and ongoing transformations enable community-driven informal learning, spontaneous contributions, and creative reuse in the Blikfabriek. This adaptivity overcomes UM barriers typically associated with applying non-uniform and non-bulk components in new contexts.

The recirculation phase demonstrated that community involvement extends beyond physical labor, playing an essential role in addressing logistical and social barriers while making circular practices socially visible. The cases demonstrate that tangible, narratable material flows strengthen social acceptance of reuse. The direct delivery of harvested components to flood victims made reuse especially meaningful and efficient. In de Pastorie, terrazzo tiles became carriers of collective memory. At the Blikfabriek, the site itself functions as a living exhibition of evolving material culture. This visibility helps shift

Table 1. Comparison of community involvement and UM barriers across each phase and case.

	Identification	Harvesting	Recirculation	Key Community Contribution:
Albert Building:	Systemic pairing of volunteers to harvestable components	High volume of harvested components without added costs	Direct reuse of harvested components for disaster relief	Coordinating volunteer efforts to provide urgent humanitarian aid, overcoming time constraints and storage bottlenecks
RTT/De Pastorie:	Socially aware and engaging harvesting and reuse	Integrating stewardship with efficiency	Participatory design narrating collective memory	Embedding socio-cultural value and agency in urban transformation, overcoming narrow valuation frameworks and socio-technical uncertainties of reuse
Blikfabriek:	Informal network of actors coordinating harvesting and reuse	Outsourcing material from determinate urban transformation cycles	Ongoing transformations valorizing cultural byproducts	Responding to spatial demands through localized reuse, overcoming structural and technical barriers associated with formal governance and design

perceptions of material reuse and strengthens cultural acceptance of circular practices while avoiding UM barriers such as material storage, logistics planning, and devaluation of materials.

However, community involvement does not solve all barriers. Well-orchestrated logistics can offset fragmentation, but such coordination depends on circumstance and committed owners and local volunteers. The RTT/De Pastorie case adopted filtering to manage standardization and emotion. The Blikfabriek's opportunistic model required time, continuous stewardship, and diverse programming. Overall, enabling community involvement requires openness combining early communication, inclusive participation,

networked collaboration, and visual storytelling to facilitate UM processes. The successful involvement of local communities in UM has the potential to revive a widespread reuse culture contributing to economic, social, and environmental sustainability.

7 Conclusion

The three cases collectively demonstrate that community involvement in UM can enhance technical feasibility, social acceptance, and alignment with circularity principles by enabling direct reuse. Early and transparent engagement clarifies constraints and motivations, aligning stakeholders around what can and should be harvested. Networked collaborations spanning citizen initiatives, makers, cultural actors, property owners, and volunteers expand capacity and solve practical bottlenecks in access, transport, and storage. Accessible, skill-appropriate participation makes UM a collaborative process that builds local capability and shared ownership. Finally, visible and narratable material flows, whether as direct aid, embedded features in public buildings, or an evolving landscape of reuse, make circularity an experience that communities can see, use, and claim.

While community involvement cannot erase regulatory, financial, or professional hurdles, it helps navigate them through distributed responsibility and continuous communication. The result is a shift towards iterative, place-based circular practices that couple material recovery with cultural and social value creation. Practically, this means designing UM processes with structured openness: engage early, mobilize networks, tailor participation, and make material journeys visible. Doing so embeds UM within broader circular urban transformations that communities can recognize as their own.

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New Sustainable Design Practice Guidelines in the Memorial Park October in Kragujevac

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Abstract. Redesign, regeneration, and reuse processes of memorial landscapes require delicate approaches that balance symbolic meaning, everyday use, ecological resilience, and long-term stewardship. While such balance can be supported through participatory planning, in Serbia these practices remain underdeveloped and have limited influence on decision-making. This research addresses this gap by translating public attitudes into applicable design guidelines that support sustainable, ethical, and context-sensitive future interventions. Within the Memorial Park "October in Kragujevac," several areas are currently neglected, providing an appropriate context for examining potential spatial interventions. The main goal is to undestand what programmatic additions in these and similar areas citizens perceive as acceptable or desirable, and how these perceptions relate preservation memorial identity preservation. Methodologically, the research has two phases. The first phase involves the analysis of primary and secondary sources documenting the current condition of selected locations within the memorial park, alongside relevant examples of good practice. The second phase consists of an empirical survey conducted with a sample of 212 participants, including local residents, park users, and visitors from different age groups. The survey is conceptualized as a supplementary tool used to test and validate proposed concepts through consultation with a broader public. Survey results indicate differentiated public preferences: more than 70% of respondents support regeneration through child-oriented programmes, while the majority oppose interventions perceived as commercially oriented or incompatible with the commemorative character of the site. By grounding future design strategies in public preferences and lifecycle-oriented thinking, the research contributes to long-term cultural, social, and environmental sustainability.

Keywords: Memorial landscape · Collaborative design · New sustainable design · Cultural heritage

1 Introduction

Memorial sites illustrate the interdependence between space and memory, as they inscribe symbolic meaning into their physical surroundings while simultaneously deriving significance from contexts in which they are situated [17, 18, 20]. Although often

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conceived as spaces of permanence and reverence, memorial sites exist within dynamic urban, ecological, and social systems. Over time, shifts in daily use patterns of memorial sites do happen. Therefore, the challenge lies in managing reuse and regeneration in ways that respect symbolic meaning while meeting contemporary needs. Balancing commemorative integrity with everyday urban life requires carefully calibrated approaches that integrate cultural, social, and ecological dimensions of sustainability. Participatory planning has been recognized as a potential mechanism for achieving this balance. This is particularly significant in sites associated with tragic historical events, where interventions may be perceived either as meaningful revitalization or as a disruption of remembrance. One such context is the Memorial Park October in Kragujevac (also known as „Šumarice"). Established in memory of the civilians executed by the Wehrmacht on 20 and 21 October 1941, the park represents a spatial embodiment of collective mourning. However, the tragedy of October 1941 was not the only layer of suffering inscribed into this landscape. Even before the Second World War, the area encompassed sites associated with casualties from the First and Second Balkan Wars, as well as the First World War, thereby embedding multiple historical traumas within the same spatial framework [18, 19]. The memorial character of the site, combined with its function as an active urban green space, makes it a particularly delicate setting for examining future interventions. This research seeks to examine which forms of change are perceived as compatible with the site's commemorative character. By translating expressed public preferences into design-oriented principles, the research aims to contribute to the development of context-sensitive, ethically grounded sustainable strategies for memorial landscape regeneration.

2 Methodology

The research is designed as a mixed-methods study comprising two phases: document analysis (qualitative) and survey research (quantitative). In the first phase of **Document analysis**, the material is reviewed, examined, and interpreted. This type of analysis constitutes the main component of the mixed methods study. It includes primary sources (decisions and meeting minutes, urban plans and projects, proposals) and secondary sources (predominantly monographs that interpret specific historical developments and decision-making processes). The aim of this phase is to present, in chronological order, the emergence, development, and modes of use and management of the space. It follows the formal and functional development of the memorial park. The second phase is the quantitative part of research. In this **Survey research**, the main instrument used is a structured questionnaire. This type of analysis serves as a supplementary tool for validating the previous research and for providing additional insight into the needs and attitudes of users regarding the regeneration of certain insufficiently treated areas of the memorial park. The paper focuses on drawing conclusions from the survey regarding: **(1)** *users' attitudes toward the current condition of the memorial park*, and **(2)** *the extent to which users are willing to accept changes resulting from spatial or programmatic interventions*. The survey included 212 respondents living in the immediate surrounding area, that is, within the Municipality of Kragujevac. The questions were formatted in two ways: as multiple-choice questions and in the form of a Likert scale. The Likert scale was used

for questions concerning users' attitudes toward the introduction of spatial interventions or programmatic changes in each zone of the memorial park. In this way, the intensity of their flexibility, willingness to accept change, and opinions on what is compatible with the park's broader memorial purpose were measured. For the purposes of interpretation, the responses were transformed into a three-point scale: disagreement with the proposed intervention, a neutral attitude, and agreement with the proposed intervention.

2.1 Phase 1: Neglected Areas Within Memorial Park "October in Kragujevac"

Research Area

Within the Memorial Park "October in Kragujevac", several spatial units remain insufficiently recognized by key stakeholders (including citizens, municipal authorities, and park management) despite their considerable developmental and symbolic potential (Fig. 1) These areas include the Military Cemetery, the Botanical Garden, the Military Command (Čomić Villa), the Czechoslovak Cemetery, and Šumarice Lake, along with additional facilities developed outside the original project concept, such as the Chapel of the Kragujevac Martyrs, Šumarice Hotel, and other programmatic interventions. **The Military Cemetery** is one of the oldest and most symbolically significant parts of the park. Established in the second half of the 19th century following the construction of the Military Hospital (1865), it contains the remains of Serbian soldiers from the Serbo-Turkish Wars and over 3,000 soldiers from the First World War. Opposite it, German military burials from both world wars were also located. Its planned spatial structure and historical layering reflect its high memorial value. However, most monuments were demolished in the 1950s for ideological reasons, with only partial restorations in the late 1970s. This destruction reflects the complex politics of memory that shaped post-war spatial reinterpretations of the site. **The Botanical Garden**, established in 1997 within the Memorial Park as part of the Faculty of Natural Sciences and Mathematics, occupies the former Saračević estate. Today, the Botanical Garden plays an important ecological and educational role, focusing on biodiversity preservation and environmental awareness. Similarly, **Čomić Villa** (temporarily the headquarters of the Serbian Army during 1914–1915) constitutes an important architectural and historical asset. Adjacent estates, including Novaković's property, were later nationalized, and the surrounding space became the site of wartime executions and post-war memorialization. Despite their historical importance, these estates lack adequate valorization within the contemporary park structure. **The Czechoslovak Cemetery** commemorates 44 Slovak soldiers executed in 1918. The monument complex, inaugurated in 1924, reflects interwar Yugoslav–Czechoslovak political alliances and features a highly articulated architectural composition, including an obelisk, sculptural elements, and landscaped viewpoints. Incorporated into the Memorial Park planning after the Second World War, it remains a peripheral yet symbolically significant memorial node. Finally, **Šumarice Lake**, created in 1964 by damming the Sušica stream, introduced a major landscape transformation not foreseen in earlier urban plans. Beyond flood regulation, the artificial lake became an important recreational and social space, later integrated into sports and municipal infrastructure. Over time, it developed into one of Kragujevac's primary gathering points, demonstrating the adaptive layering of memorial, ecological, and recreational functions within the park.



Fig. 1. Map of several units in need of urban regeneration due to inactivity.

Current State Analysis

The establishment and early development of the Memorial Park "October in Kragujevac" have been addressed in several academic and professional studies, which document the competition phase, the preparation of the Master Plan, and the gradual institutionalization of the complex as a site of national memory [1]. The park's status was formally consolidated by the 1979 decisions of the National Assembly of the Republic of Serbia**,** declaring it a cultural monument and an immovable cultural property of exceptional significance [2, 3, 4]. These acts elevated the site to the highest level of heritage protection and defined its importance within the national commemorative landscape. Subsequent changes in the legislative and planning framework have shifted jurisdiction to the republican level, foreseeing the preparation of a Spatial Plan for an Area of Special Purpose. The original development unfolded in two principal stages: the architectural and urban design competition, followed by the adoption of the Master Plan for the park's comprehensive realization. Numerous components of the complex (e.g. monuments, cemeteries, natural features, and programmatic units) are documented in the Lexicon of the City of Kragujevac, reflecting the layered structure of memorial, cultural, and landscape elements embedded within the park [5–8]. Research on specific segments of the complex remains uneven. **The Military Cemetery** in Šumarice has been the subject of a monograph by Nenad Karamijalković, as well as archival and field data compiled by Momčilo Marinković [9–11]. **The Botanical Garden**, established institutionally through decisions of the City Assembly in the 1990s and entrusted to the Faculty of Science of the

University of Kragujevac, is supported by detailed urban plans, investment programmes, and phased project documentation. Today, its planning framework is governed by the General Regulation Plan "Central City Park Šumarice" situating it within the contemporary urban planning regime [12]. Information on **Čomić Villa** is primarily derived from architectural historiography, notably the works of Veroljub Trifunović [13]. The **Czechoslovak Cemetery** is documented in interwar studies and Slovak historiography [14]. In contrast, **Šumarice Lake** remains insufficiently researched [15]. Aside from technical documentation related to the 1964 dam construction and references in urban planning documents, only brief historical accounts exist in studies of post-war urban development. This uneven state of scholarship indicates the need for a more integrated, interdisciplinary approach that would connect legal, urbanistic, architectural, and museological perspectives in the future governance and interpretation of the Memorial Park as a complex cultural landscape.

2.2 Phase 2: Survey and Local's Opinions on Future Interventions

Although the park has a strong memorial character, it is also the largest landscaped green area in the Municipality of Kragujevac and serves as an important everyday public space for recreation, including walking, socializing, and spending time with children. Users' attitudes toward the current condition of the park and the potential directions in which it could develop represent valuable information on how culturally and historically sensitive spaces that also serve as significant socio-ecological resources can be planned. The results show that the largest percentage of respondents (40%) believe that certain parts of the park should offer additional facilities. A somewhat smaller number of respondents consider the current range of facilities satisfactory, approximately 20% believe that the park as a whole lacks sufficient facilities, and the smallest percentage (4%) believe that the park landscape has been compromised by an excessive number of facilities. In addition to facilities, perceptions of the park's provision of urban furniture were also examined. As many as 55.4% of users believe that certain parts of the park should contain a greater number of benches, waste bins, lighting elements, and similar features. Respondents' visions of possible future scenarios indicate the following results: 71.7% of all respondents believe that spaces for children should be arranged and designed, while 59% believe that the number of promenades and fitness trails should be increased. At the same time, the largest share of users (75.5% and 83.5%) believe that it is necessary to complete the design of the memorials on all mounds (at present, only 14 out of 30 have been artistically treated and completed) and even to expand the memorial park's program to include the period before the Second World War. In addition, 61.8% believe that it is not appropriate to provide dedicated areas for picnics, barbecuing, and larger gatherings. Based on this, it may be concluded that the primary purpose of the memorial park is not lost from users' perception at any point, and that they are able to recognize compatible facilities. The results show that the zones in which intervention is considered most acceptable are the area around Lake Šumarice (60.9%) and the area around the Botanical Garden (52.8%), which are already the zones with the greatest spatial, programmatic, and ecological potential for further improvement. By contrast, zones with a dense memorial character are perceived as the least suitable for intervention (47.6%).

3 Results: Public Sentiment Shaping the Design Guidelines for Sustainable Memorial Landscape Regeneration

For the purposes of this study, public sentiment is treated as a key analytical category that reveals how local communities perceive acceptable transformations within memorial space. Since 55.4% of respondents support additional benches, waste bins, lighting, and similar amenities, the results indicate that certain parts of the park are expected to accommodate everyday use, provided that such improvements remain compatible with its commemorative character. The document analysis indicates that the park has developed through multiple complex historical layers and spatial transformations. A key finding is that users distinguish varying levels of sensitivity within the park. Zones with a pronounced memorial character are perceived as areas requiring a stricter protection regime, while interventions in parts with greater ecological or recreational potential are considered more acceptable. This highlights the importance of a zoning-based spatial approach, where park areas are managed according to their memorial significance, ecological value, and capacity for public use. Memorial parks dedicated to sites of suffering are highly sensitive spaces for local communities. While citizens seek to maintain their everyday connection to these areas, they also support the restoration of memorial elements. Future interventions should therefore ensure public participation and require a binding study as part of planning documentation, helping to establish trust between institutions and citizens.

4 Discussion and Conclusion

The comparison between professional assessments and public perceptions highlights key directions for sustainable, context-sensitive design. Both perspectives support preserving areas of high memorial significance while allowing more flexible interventions in zones with greater ecological and programmatic potential, particularly around Lake Šumarice and the Botanical Garden. In this regard, a key spatial strategy is the implementation of a tiered zoning system that differentiates park areas according to memorial importance, ecological value, and capacity for public use. As a cultural landscape recognized as an immovable cultural property of exceptional significance since 1979, the park requires a governance framework that integrates national and international heritage protection regulations with local spatial planning instruments. An essential step in this process is the adoption of a Spatial Plan for an Area of Special Purpose. Under the current Serbian Law on Planning and Construction [20], the preparation and funding of this plan fall under the responsibility of the Agency for Spatial and Urban Planning of the Republic of Serbia, while its final adoption is carried out by the Government of the Republic of Serbia. Although repeatedly requested by the City of Kragujevac, funding has not yet been secured. Future planning processes should be supported by a strengthened mandate for the New Memorial Park Commission, responsible for overseeing planning procedures, conservation standards, and risk management, while ensuring transparency through systematic documentation and public reporting of interventions. Future design guidelines should prioritize ecological sustainability and biodiversity. In the Šumarice Lake zone, water-sensitive urban design through constructed wetlands and vegetative buffer strips

should be applied. Within the Botanical Garden, rewilding and permaculture areas could support self-sustaining landscape functions while enhancing education and visitor experience. Biomass should be managed on-site: branches can be shredded into mulch, while larger timber can be reused as building material. This lifecycle-oriented approach supports circular economy principles by treating local waste as a resource. At a larger scale, selective deconstruction should replace demolition, with interventions following Design for Disassembly principles through modular pavements, flexible zoning, and removable pavilions. Adaptable urban furniture made from upcycled materials and, where appropriate, smart off-grid elements can further reduce environmental impact. Combined with community participation, these measures can enhance the park's ecological, social, and recreational value while preserving its commemorative identity.

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Comparative Case Analysis of Waste Sorting and Processing Models for Advancing Circular Construction in Europe

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Abstract. Construction and demolition waste (CDW) represents one of Europe's largest materials flows and a critical challenge for achieving circularity in the built environment. Drawing on comparative case studies from Latvia, Estonia, Greece, Cyprus, Slovenia, Romania, and Turkey, this paper analyzes how diverse CDW management models: centralized recycling hubs, on-site demolition processing, closed-loop manufacturing systems, public-led circular construction initiatives, and digital or technology-enabled waste prevention strategies influence material recovery outcomes, environmental performance, and market dynamics. Using a structured cross-case analytical framework, the study compares technological, regulatory, and operational features across cases to understand how collection, sorting, and processing systems shape circularity potential. Results demonstrate that advanced automated sorting, integrated value-chain models, and digital tools can substantially increase landfill diversion rates, reduce CO_2 emissions, and preserve virgin resources. However, persistent barriers including insufficient market demand for secondary materials, lack of end-of-waste criteria, regulatory inconsistencies, and cultural resistance, limit broader uptake. Stakeholder insights further

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highlight the role of political incentives, economic competitiveness, and technological readiness in enabling or constraining CDW circularity. The findings contribute to a clearer understanding of how European CDW sorting and processing practices can support a high-value circular construction transition and identify priority areas for policy and industry action.

Keywords: Construction and Demolition Waste (CDW) · Circular Construction · Waste Sorting and Processing · Secondary Raw Materials · Recycling Technologies · Industrial Symbiosis · Circular Economy Models

1 Introduction

Construction and demolition waste (CDW) constitutes a major global waste stream and is widely reported to represent 30–40% of total waste generated worldwide [7, 11]. Although the European Union has introduced regulatory instruments and recovery targets, the sector continues to face challenges related to fragmentation, inconsistent regulatory enforcement, and limited market demand for secondary materials [6].

Studies examining global CDW trends emphasise that rapid construction activity and inadequate waste management practices significantly increase waste loads and environmental pressures [5]. In parallel, systematic reviews of CE strategies in CDW demonstrate that circularity depends on coordinated interventions across demolition practices, sorting infrastructure, and secondary material market development [8]. Research on recycled concrete aggregates further shows that these materials can effectively replace natural aggregates with acceptable structural performance when properly processed [1], contributing to measurable reductions in CO_2 emissions [9]. CDW valorisation supports sustainable business models by enhancing resource efficiency and enabling closing-the-loop strategies, as outlined by Bocken et al. [2].

A growing body of research highlights selective demolition [3], automated sorting technologies [12], and material-specific closed-loop recycling processes such as concrete and gypsum recovery [13] as key enablers of improved circularity. However, most scientific contributions focus on single technologies, individual material streams, or isolated national contexts. As a result, limited attention has been given to how different CDW management models perform under contrasting operational, regulatory, and market conditions across Europe. This paper addresses this gap, through a comparative analysis of fourteen operational CDW management cases from seven countries. The study examines how technological configuration, logistics organization, governance support, and market conditions shape material recovery efficiency, circularity outcomes, and overall system performance. It also identifies the enabling conditions and systemic barriers that influence the scalability of high-value recycling practices. The central argument emerging from the comparison is that strong circularity performance depends not on technology alone, but on the alignment between sorting capacity, market demand, regulatory clarity, and proximity-based reuse opportunities.

2 Methodology

The methodology was designed to ensure a systematic, transparent, and comparative assessment of CDW management models across seven European and neighbouring countries. Fourteen case studies were selected on the criterion that each must represent an operational, documented CDW sorting or processing activity, including facilities in Latvia, Estonia, Slovenia, Cyprus, Greece, Turkey, and six Romanian cases covering demolition-based recovery, cement co-processing, closed-loop material systems, and manufacturing reuse strategies. Scientific publications were used to interpret technological performance and situate findings in broader circular economy research.

A structured analytical framework of five interconnected dimensions was applied: (1) collection and logistics organization; (2) sorting and processing technologies; (3) circular economy contribution and material loop integration; (4) measurable performance indicators such as recovery rates, diversion rates, and CO_2-related impacts; and (5) enabling conditions and constraints, including regulatory environments, market factors, and public-sector support. Cases were coded according to this structure and categorized into five CDW management model groups: centralized high-automation hubs, on-site demolition processing systems, industrial closed-loop or co-processing systems, public-led circular construction hubs, and digital-enabled or technology-driven circularity systems.

This approach enabled synthesis of heterogeneous case information into a cohesive comparative assessment evaluating both how CDW is managed and what impacts these models produce under real operational conditions. The comparison is constrained by differing reporting formats and indicator availability. Indicators such as diversion rates were not normalized but reported as provided by each source; cross-case comparisons should therefore be read as indicative rather than strictly equivalent.

3 Results

The fourteen case studies examined in this research represent a wide spectrum of operational approaches to CDW management. The CDW case studies show substantial variation in logistics, technological maturity, and integration with industrial processes. Centralized high-automation hubs, including CleanR Verso in Latvia and Green Marine AS in Estonia, report diversion rates above 70% and produce multiple certified fractions, though their effectiveness depends heavily on stable waste inflows and functioning market demand. In contrast, on-site demolition systems such as BS Recycling in Romania reduce transport-related emissions and enable immediate reuse of aggregates, albeit with fewer and less refined material fractions. Closed-loop industrial systems, for example, gypsum recycling by Saint-Gobain or ceramic reuse by Wienerberger, achieve high material purity and predictable output quality by reintegrating CDW into established manufacturing processes. Public-led circular hubs, such as Nigrad in Slovenia, demonstrate how municipalities can use CDW to support territorial regeneration and localized reuse loops. Digital-enabled models, including blockchain-based concrete monitoring and CO_2-reactive aggregate upgrading, illustrate innovative mechanisms for waste prevention and quality improvement, though they remain in early implementation stages.

Collectively, the results show that CDW performance outcomes arise from interactions among logistics, technological capacity, market structure, and regulatory conditions.

By grouping the cases according to shared operational principles, the analysis provides a clearer understanding of how different models contribute to Europe's circular construction transition and how each model's strengths and constraints shape its performance. The aim is not to reduce the complexity of each case but to make visible the structural relationships between organizational form, technological infrastructure, and circularity outcomes.

Table 1. Summary of CDW management model types and representative cases.

Model type	Representative cases	Key operational characteristics
Centralized high-automation hubs	CleanR Verso (Latvia); RRC Fasoula (Cyprus); Green Marine AS (Estonia); Romania Mixed Facility A; Romania Mixed Facility B; Romania Mixed Facility C	Large-scale mixed CDW reception; automated mechanical and sensor-based sorting; high throughput capacity; stable secondary material outputs.
On-site demolition processing systems	BS Recycling (Romania)	Mobile crushing and separation equipment brought to demolition sites; reduced transportation needs; immediate reuse of aggregates in infrastructure projects.
Industrial closed-loop / co-processing systems	Geocycle (Romania); CRH (Romania); Wienerberger; Saint-Gobain Rigips (Romania)	Integration of CDW into cement kilns or manufacturing lines; processing of non-recyclable fractions as alternative fuels or feedstock; mono-material recycling loops (gypsum, clay products).
Public-led circular construction hubs	Nigrad / Maribor CE Hub (Slovenia)	Municipal reuse and recycling operations; reclaimed materials used in local building, road, and embankment projects; community access to secondary raw materials markets.
Digital-enabled and technology-driven systems	SKYRODEMA (Greece); CO_2-reactive aggregates (Turkey)	Blockchain-enabled traceability, fresh concrete waste prevention, accelerated carbonation, and material upgrading technologies.

Table 1 ssummarizes the five model types identified in the comparative analysis and highlights the operational logic that differentiates them. Centralized high-automation

facilities possess strong material-sorting capabilities and deliver high-quality recycled outputs but depend heavily on consistent waste inflows and supportive market conditions. On-site demolition systems function effectively in large-scale demolition projects and significantly reduce the environmental burden associated with material transportation. Industrial closed-loop systems are highly efficient for specific material flows, such as gypsum or brick residues, though they are constrained by their reliance on uniform waste types and internal industrial demand. Public-led hubs demonstrate how municipal actors can use CDW management to revitalize degraded areas, develop local reuse markets, and support community-level circularity. Finally, digital-enabled models offer novel approaches to waste prevention and quality enhancement, although most remain at early stages of practical adoption. Taken together, these models illustrate the diversity of pathways available for improving CDW management in Europe. They also demonstrate that circularity can be achieved through different forms of governance, technology, and business models, depending on local conditions, material streams, and institutional capacity.

The case studies reveal that performance differences among CDW systems arise primarily from how waste is collected, transported, and sorted, and from the technological maturity of processing infrastructures. Centralized high-automation hubs such as CleanR Verso in Latvia and Green Marine AS in Estonia rely on structured logistics that consolidate mixed waste flows into large-scale sorting facilities, where automated optical sensors, magnetic separators, and multi-stage mechanical systems enable diversion rates above 70% and the production of multiple certified fractions. In contrast, mobile on-site processing, represented by BS Recycling in Romania, integrates demolition logistics with material recovery at the source, minimizing transport emissions and enabling rapid reuse of aggregates in nearby infrastructure projects. Cyprus applies a hybrid model where partial on-site sorting is supported by centralized mechanical and manual separation, illustrating how mixed systems evolve in regions with fragmented markets and developing regulatory frameworks.

Differences in sorting technologies strongly influence circularity outcomes. High-automation lines in Latvia and Estonia demonstrate superior precision and throughput, whereas material-specific loops, such as Saint-Gobain's gypsum recovery and Wienerberger's ceramic reuse, achieve high purity and full reintegration of CDW into industrial manufacturing cycles. Co-processing facilities in Romania and Turkey extend circularity into cement production by converting CDW into alternative fuels or clinker substitutes, with the Turkish carbonation process additionally reportedly capturing up to 250 kg CO_2 per tonne of aggregate processed. Digital technologies introduce new forms of circularity: Greece's blockchain-based system prevents fresh concrete waste by tracking its age and redirecting surplus material before hardening, reportedly achieving nearly full recovery of aggregates.

Circular economy contributions differ across contexts. Municipal reuse hubs such as Nigrad in Slovenia demonstrate high levels of local material recirculation, in some reported applications reaching 100% reuse for specific fractions, by integrating CDW into public works and urban regeneration projects. Industrial closed-loops generate high-value products such as plasterboards and bricks, while centralized hubs predominantly supply recycled aggregates to construction markets. Environmental benefits include

reduced emissions from avoided virgin extraction and transport optimization, particularly in Slovenia and Turkey, where material loops operate within short geographic radii. Social and economic impacts vary: job creation is evident in Latvia, Estonia, and Slovenia, while Cyprus demonstrates that even well-designed systems face severe limitations when market demand for recycled materials is low. These findings collectively show that system performance depends on the alignment of logistics, technology maturity, market structure, and regulatory clarity. This relationship is synthesized in Table 2.

Table 2. Summary of CDW model outcomes across case studies.

Model type	Observed outcomes
Centralized high-automation hubs	High diversion rates (70–80%+); multiple sorted fractions; strong output quality; dependence on market demand and steady inflows.
On-site demolition processing systems	Reduced transport emissions; immediate reuse; fewer output fractions; variable purity depending on demolition conditions.
Industrial closed-loop / co-processing systems	Stable integration into industrial processes; substantial substitution of virgin fuels and materials; high predictability; limited to specific waste streams.
Public-led circular construction hubs	Localized reuse; territorial regeneration; community access to materials; strong circularity for specific fractions.
Digital-enabled and technology-driven systems	Waste prevention; improved traceability; enhanced material properties; early-stage scalability but high innovation potential.

The comparative patterns summarized in Table 2 indicate that no single model dominates across all dimensions of circularity. Instead, performance depends on the interplay between technological capability, proximity-based logistics, regulatory support, and market readiness. Centralized hubs excel at material purity, on-site systems minimize emissions, closed-loops create stable industrial demand, public hubs localize circularity, and digital models prevent waste formation altogether. Together, these models highlight complementary pathways toward a more resilient and higher-value circular CDW system.

4 Discussion

The findings indicate that technological capacity alone does not determine CDW circularity; effectiveness depends on the alignment of sorting technologies, market readiness, and clear regulatory requirements. High-performance automated sorting systems support previous that sensor-based separation can significantly improve material recovery

quality [4, 12]. However, their impact remains constrained where demand for secondary materials is weak, as illustrated by the Cyprus and Romanian cases. Public-led reuse models, exemplified by Nigrad in Slovenia, show how local governance and municipal strategies can strengthen circular loops, while fragmented regulatory enforcement in Romania and the absence of end-of-waste criteria in Cyprus reflect structural barriers identified in previous research [7, 10]. Emerging digital innovations, such as blockchain traceability and CO_2-reactive aggregate upgrading, also appear promising for waste prevention, real-time quality verification, and lifecycle tracking, although their large-scale deployment remains limited. It should also be noted that scaling digital-enabled systems such as blockchain traceability to less digitally mature markets may face significant barriers, including high implementation costs, limited digital infrastructure, and low digital literacy among construction sector actors. Phased deployment models and targeted public investment would likely be required to extend such innovations beyond well-resourced pilot contexts across European regions. Overall, the comparison suggests that resilient CDW systems require not only technological advancement but also coherent policy frameworks, functioning end-markets, stakeholder awareness, and proximity-based reuse loops. The persistence of cultural and social barriers, particularly about the safety of recycled aggregates, further underscores the need for targeted education, certification systems, and market-building measures.

This study has several limitations. The cases are heterogeneous in scale, maturity, reporting depth, and regulatory context, which limits direct standardization of performance indicators across all models. In addition, some cases are reported through project or case-specific documentation rather than uniform datasets, meaning that the comparison should be interpreted as an analytically structured cross-case assessment rather than a statistically harmonized benchmark. Future research could strengthen the evidence base by applying common circularity indicators and longitudinal monitoring across a larger number of cases.

5 Conclusions

This comparative case study demonstrates that European CDW management systems are diverse, evolving, and increasingly oriented toward circularity. Centralized hubs excel in producing high-quality secondary materials, on-site demolition systems reduce transport-related impacts, industrial closed-loop processes secure stable material inputs for manufacturing, public-led hubs stimulate territorial circularity, and digital innovations enhance traceability, quality, and waste prevention.

Despite these advancements, persistent challenges remain. Market acceptance of secondary materials is inconsistent, regulatory frameworks are fragmented, and cultural reservations about recycled products undermine adoption. Technological readiness also varies widely across regions, and end-of-waste criteria remain unclear in several national contexts. For circular construction to become standard practice, policy and industry action should prioritize at least four areas: harmonized end-of-waste criteria, stronger quality certification and traceability systems, public procurement requirements for recycled materials, and targeted investment in selective demolition and advanced sorting infrastructure. Of these, harmonized end-of-waste criteria represent the most

foundational priority for regions currently showing regulatory inconsistencies – such as Romania and Cyprus – as the absence of clear end-of-waste status undermines market confidence in secondary materials and limits the effectiveness of the three remaining measures. Quality certification, public procurement, and sorting investment can only deliver systemic impact once a stable and consistent regulatory baseline is in place

No single model offers a universal solution. However, the comparative evidence shows that the strongest circularity outcomes emerge where technological capacity, stable-end markets, supportive regulation, industrial collaboration, and traceability mechanisms are aligned within locally appropriate reuse and recycling systems.

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Categorisation of the Building Stock of Great Britain on a Building Use Archetype Level

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Abstract. Within the BuildZero research program, we are exploring the extent to which the UK's future building needs may be met with zero material extraction, zero waste and zero carbon emissions. A first step in this mission is to gather a better understanding of the UK building stock, including: use types, construction form, building geometry, and variation of these factors by location. This paper explores the analysis of the existing building stock of Great Britain at a building use level, utilising building information from the Ordnance Survey National Geographic Database (OS NGD). Key geometrical attributes, such as the number of floors and the footprint area of the building, for example, have been investigated to determine what a 'typical' building of each use would look like, investigating how this varies by location across Great Britain. The ultimate aim of this is to use information on the structural form of different use types to assess adaptive reuse potential. The current building stock contains a wide variety of structural forms, ranging from 1–2 storey masonry brick housing to multi-storey frame structures. The prevalence and configuration of different frame types for building use classifications has been explored in an expert consultation workshop with practicing structural engineers. This paper presents these combined findings for the building stock of Great Britain, as the first step in identifying widespread adaptive reuse and component reuse potential, which will be undertaken during the remainder of the BuildZero project.

Keywords: Buildings · Stock · Adaptive reuse · Frame structures · Circularity · Urban mining

1 Introduction

The UK is home to the oldest housing stock in Europe, [1], which has been slowly changing over time and features a wide variety of building structures, ranging from 1–2 storey masonry brick housing to multi-storey steel and concrete frames. Understanding what the UK building stock is comprised of is a key topic of interest within the research community and industry, as it feeds into many aspects of the built environment, for example assessing energy efficiency, flows of materials, and structural demands of our buildings. Furthermore, there are growing pressures that require the UK building stock to adapt and change: the increasing demand for new, affordable housing, as well as a drive

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for more sustainable building practices, such as more efficient use of materials/space. Currently, there is a tension between housing targets and the environmental impacts of new construction. However, a lower impact alternative is the adaptation of our existing building stock, and thus knowing what our UK buildings look like is vital.

Modeling of the UK building stock is a prevalent area of research, typically focusing on the flow of material stocks [2–5] and/or energy and carbon efficiency [6–9]. The principal approach adopted in many of these papers follows a bottom-up approach, whereby the UK material stock is considered at a building level and scaled to give regional/national insights. Many of these works utilise satellite imagery to infer the built landscape and/or apply assumptions to what a typical building within each use category may look like from statistical data.

In contrast, this work uses the Ordnance Survey National Geographic Database (OS NGD), which provides a wealth of data on the attributes of buildings within Great Britain. This paper groups together buildings of similar use for clarity, and key information, such as number of storeys, gross floor area (GFA) distributions, as well as variance of these factors by location have been investigated. The findings of this paper will then feed into future BuildZero work, which will analyse how our existing building stock can be adapted to meet the needs of society. This work is particularly important from a structural perspective, as the overall geometrical configuration of a building has a direct relationship to the overall capacity of the structure, and therefore the potential reserve capacity for adaptive reuse potential.

2 Methodology/Data Collection

In this section, the methodology used to analyse the building stock is detailed, which has been conducted on a building use archetype level using a bottom-up approach. This work utilised the OS NGD, which is a structured database of geospatial data for Great Britain, providing a wealth of knowledge and attributed data ranging from land usage to transport networks. The OS NGD is collated from a collection of different data sources, and can be accessed from a single reference point [10]. In Fig. 1 below, the hierarchy of the database is shown for the relevant attributes used within this work, with further information available from [10].

2.1 Extraction of Data

In order to group similar buildings together, the ‘buildinguse’ attribute has been used as the main comparison point. In the instances where a building has not been assigned a ‘buildinguse’ attribute, the ‘buildinguse_oslandusetiera’ attribute, i.e. classification of the land use, will be used in its place. If neither a building nor land use is present, the building is marked as ‘unknown’. If there is more than one building use present, the ‘mixed-use’ classification has been applied. There are 28 building use classifications in total, that have been grouped as shown in Fig. 2.

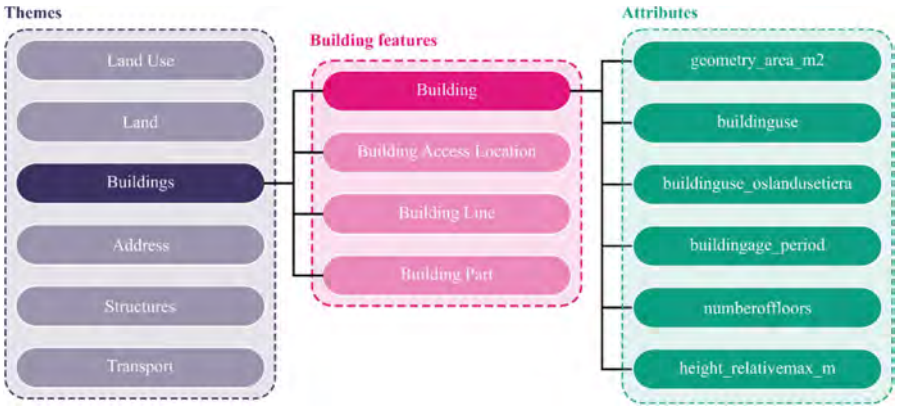


Fig. 1. Hierarchy of data within the OS NGD. Attributes for this paper are shown in green on the right and have been taken from within the 'Building' feature within the 'Buildings' theme.

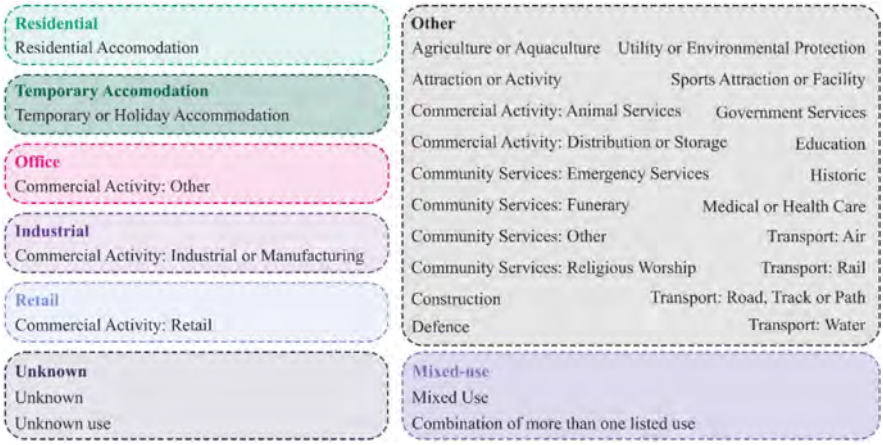


Fig. 2. The building usage classification groupings used in this study.

2.2 Splitting Data Geographically

This paper also investigates how the results vary by location. The potential significance of location was highlighted in a recent frame structures workshop, held by the BuildZero team with industry experts, who identified that they believed location played a key factor in the types of buildings present, with London being highlighted as a main outlier. To explore this factor within the NGD dataset, the building stock was divided into subgroups based on ceremonial county boundary lines, with the proportion of building uses within these analysed.

3 Results

3.1 Number of Buildings

There are 30,764,794 buildings within Great Britain, excluding domestic outbuildings (~9.8 M) and ancillary buildings (~1.1 M), which refer to external outhouses that are not part of the main building for residential and non-residential respectively, and have not been considered within this work. Figure 3 shows the breakdown of each identified building use, along with a pie chart to show the constituents of the 'mixed-use' classification.

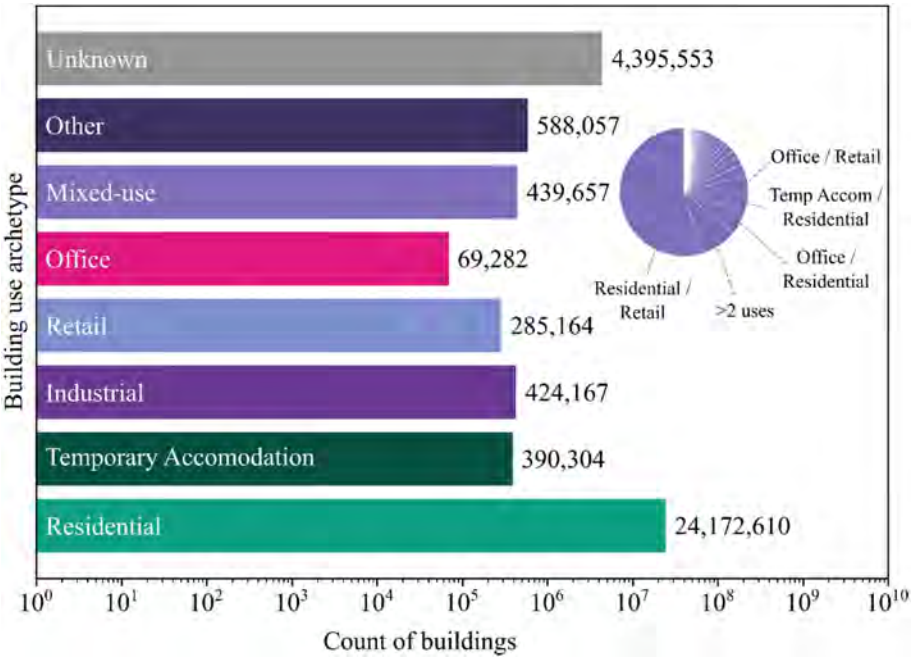


Fig. 3. Building counts for each of the building use archetypes, with a pie chart breakdown of the mixed-use category. Note the log scale on the axis for count of buildings.

The large majority of the building stock is 'Residential', which accounts for ~79% of the total buildings. The second biggest use group is 'Unknown' at around ~14%, which represents around ~4.4 M buildings. This highlights the need for accurate recordings of all buildings use, as these missing building use classifications may have a significant effect on the distribution of buildings if they were accounted for correctly. All remaining buildings account for ~1% each, with 'Office' representing the smallest building use archetype.

3.2 Number of Storeys

The vertical landscape of buildings can be represented by the number of floors/storeys within a given building. Figure 4 shows the distribution of the number of floors across

the building stock, as well as the proportion of the building use archetypes within each category.

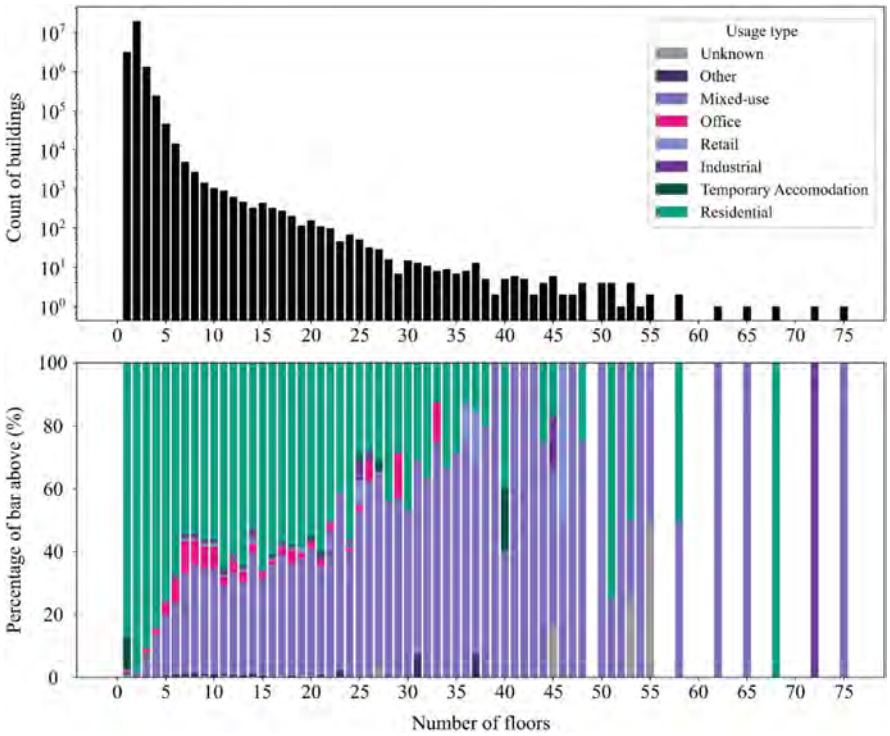


Fig. 4. Number of floor distribution for the building stock, with top graph showing the count values for each number of floors category, and the bottom graph detailing the makeup of each category based on use type. Note the log scale on the y-axis for the top graph. Buildings with an unknown number of floors were omitted from the plot as not to skew the results, which was around ~6.5 M buildings (21%).

As shown, 'Residential' remains the primary use type for buildings under ~20 floors, after which, 'Mixed-use' becomes the most prominent use type. 'Temporary accommodation' is present mainly in the single floor category, with a few other concentrations at 27 and 40 floors, whereas other use types seem most dispersed across the range of floors.

3.3 Gross Floor Area Distribution

This section explores the total floor area within buildings, also known as the Gross Floor Area (GFA). Within the dataset, this can be found by multiplying the 'geometry_area_m2' attribute by the 'numberoffloors' attribute, to give the GFA. It is noted that this may be an over-estimate of the total floor area in a building, by assuming a given

number of floors across the entire building. Buildings with no 'numberoffloors' attribute have been omitted from this plot.

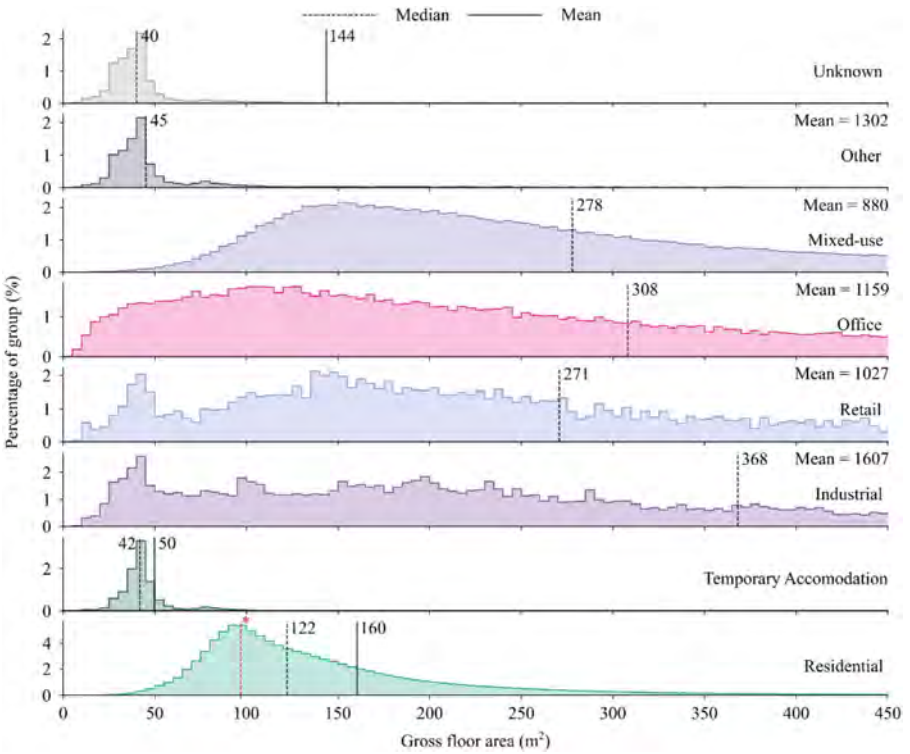


Fig. 5. Gross floor area (GFA) distribution graphs for each building use archetype, with the y axis of each plot representing the proportion of buildings within each group at the given height on the x axis. Median and mean values are also annotated for reference, as well as the average housing size (*) stated in [1]. Buildings with an unknown number of floors were omitted from the plot as not to skew the results (~6.5 M buildings or 21%).

It can be seen from Fig. 5 that 'Temporary Accommodation', 'Other' and 'Unknown' have relatively small distribution ranges that are concentrated around the lower end of the GFA scale. 'Residential' also has a bell-curve shaped, but slightly skewed distribution, at the lower end of the scale, indicating that the general space each of these provides is on the smaller side. The average housing size given in [1] has also been annotated in Fig. 5, showing good agreement with the most common GFA in NGD. 'Industrial', 'Retail', 'Office' and 'Mixed-use' use types, i.e. the main commercial activities, have the largest distribution curves, with a much wider variety of space being provided. For all use types, the mean value is larger than the median, indicating larger buildings are skewing the data set, particularly in the 'Other' use category.

3.4 Variation by Location

It has been highlighted that location may be a determinant factor for the types of buildings we have across Great Britain. To investigate this, Fig. 6 shows the breakdown of the building stock by ceremonial county boundaries, split by the percentage count of buildings (left) and the percentage space these buildings provide (right).

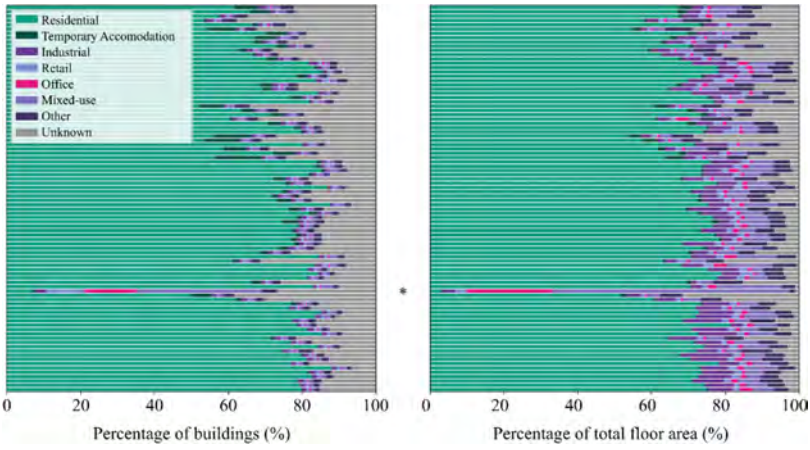


Fig. 6. Breakdown of Great Britain ceremonial counties by the percentage count of buildings (left) and the percentage of space these buildings provide (right). * City of London outlier.

As illustrated on the left, most ceremonial counties have a similar makeup of building use types, with 'Residential', 'Temporary Accommodation' and 'Unknown' being the only categories that appear to change in proportion. The 'City of London' is an outlier, with a significant reduction in the number of residential buildings and instead a higher concentration of the other building use types. However, it should be noted that this ceremonial county is the smallest and only contains around 3000 buildings. On the right, we see a similar trend for total space, however, the proportion of total space occupied by use types other than 'Residential' increases.

4 Concluding Remarks

To conclude, the building stock of Great Britain has been categorised at a building use archetype level, to give insights into the distribution and configuration of UK buildings, with regards to their count, number of storeys, and gross floor area (GFA). This showed that building use classifications, such as 'Residential', can be relatively easy to predict, as their trends generally follow a normalised distribution curve, whereas 'Mixed-use' for example includes a lot of nuance and has a much wider range of configurations.

Another key finding is the investigation into the role location plays on building use archetype results. It was demonstrated that outside the 'City of London' ceremonial county, which can be identified as a clear outlier, the overall proportion and space provided by each of the building use archetypes is fairly evenly distributed and common

across all ceremonial counties. In addition to this, the comparison between count and amount of space provided by each building use archetype highlighted that the groups of 'Industrial', 'Retail', 'Office' and 'Mixed-use', which have a relatively low count of buildings (~4%), but actually contribute to a significant proportion of the overall space within our buildings (~16%). It should also be noted that this study highlights the amount of 'unknowns' that are present within the dataset, and the need for more accurate and continuously up-to-date building information.

The overall impact of building use archetype level information allows us to analyse and understand the current existing building stock and map potential adaptive reuse approaches to their most suitable areas/archetypes, to meet the demands for additional space within our UK buildings. For example, if it was assumed that every office in the UK could be vertically extended by a single storey, assuming the average floor space of 376m^2 provided per storey, this would make around ~26 M m^2 of additional space. Alternatively, if 50% of offices were converted to residential, and an average housing size of 100m^2 was assumed, this would generate an additional ~400 k homes.

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Comparative Assessment of CDW Management and Disaster Response: Background Analysis for Material Passports

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Abstract. Construction and demolition waste (CDW) has been globally recognized as one of the most challenging waste streams, while simultaneously offering significant potential for valorization as secondary material resource. To effectively utilize these sources in their end-of-life stage, systematic characterization and robust management strategies are essential. In this context, this study comparatively evaluates the current state of CDW management approaches across the selected EU member states (Cyprus, Estonia, Greece, Latvia, Romania, and Slovenia), Switzerland, and Türkiye, with the objective of supporting the development of CDW material passport systems. The study includes characterization of the CDW streams, analysis of waste statistics and identification of good management practices within these countries, to develop realistic baselines for secondary material indicators at an international level. Furthermore, emergency action plans

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implemented during uncontrolled demolition scenarios, including natural disasters, are benchmarked to identify the operational gaps between standard waste management procedures and crisis response mechanisms. Consequently, the study highlights the urgent need to develop specialized management frameworks that prioritize each component of CDW, even when present in a mixed state, enabling their treatment as valuable secondary resources rather than a burden.

Keywords: Construction and Demolition Waste (CDW) · Material Passport · Disaster Waste Management · Circular Economy · Secondary Raw Materials

1 Introduction

Construction and demolition waste (CDW) is a challenging waste stream due to its mixed composition, difficulty of processing, and large volumes, which can be generated by controlled demolition or renovation work, as well as by natural disasters. This waste stream, the generation of which is largely unavoidable, consists primarily of a mineral waste fraction composed of concrete, bricks, tiles, and ceramic components; plastics; metals; glass; wood; plaster; and insulation materials. These wastes are classified under section 17 of the Waste Code List, defined in 1994 as the European Waste Catalogue (EWC) and renamed the List of Waste (LoW) in 2000 with the updated EU legislation. Regulation (EC) No 2150/2002, published by the European Union in 2002 [1], requires member states to maintain and report waste statistics in EWC-Stat format. However, there are discrepancies in the reporting of CDW statistics among many member states. Despite the data inconsistencies, a report published by the Joint Research Centre (JRC) in 2024 states that nearly 40% of the waste produced in the EU is CDW and the largest share of this waste, excluding excavated soil, belongs to the mineral fraction, with a rate of 77% [2]. The 2008 EU Waste Framework Directive (WFD) [3] sets a 70%-by-weight target by 2020 for reuse, recycling, and other material recovery — including backfilling — of non-hazardous CDW, excluding naturally occurring material under LoW 17 05 04, thereby defining both the quantitative target and the hierarchy in scope. According to Eurostat statistics, the overall recovery rate in the EU was reported at 89% in 2020, but this rate is largely due to member states including backfilling practices in their recovery rate calculations, despite varying definitions and scopes [2].

To eliminate this dependence on low-value recovery and align with the Circular Economy Action Plan (2020), the EU policy framework is shifting its focus from quantity to the quality of recycling. The aim is to keep materials in the loop for as long as possible at their highest value and to promote the secondary raw materials market. However, the biggest obstacle to high-quality recycling is the lack of reliable data on the composition and quality of CDW. In this context, Material Passports (MP) have emerged as critical tools for ensuring traceability, quality assurance, and the separation of hazardous substances at source, and this study aims to assess whether selected countries are ready for MP implementation by comparatively evaluating their CDW management baseline criteria, while also addressing operational gaps in managing these flows under uncontrolled disaster conditions.

2 Methodology

This study adopts a comparative analysis approach covering eight countries with different economic and geographical characteristics. Six of these countries are EU members (Cyprus, Estonia, Greece, Latvia, Romania, and Slovenia), while Switzerland and Türkiye, which are outside the EU, are also included in the analysis. Data on CDW production, composition, and recovery rates were collected from national databases, agency reports, and expert inputs; where source statistics permitted, excavated-soil flows (LoW 17 05 04) were reported separately from the structural mineral fraction to improve cross-country comparability. The collected data were synthesised against four comparative indicators — data availability, EoW circularity, sorting-technology readiness, and disaster-response maturity — to score each region's readiness for Material Passport (MP) adoption.

3 Results and Current State Assessment

3.1 Quantitative Analysis of CDW

Analysis of data collected from partner countries and the relevant literature reveals significant heterogeneity in CDW generation rates. This heterogeneity is largely due to differences in construction intensity and the geological classification of excavated materials. In line with the European average, the mineral fraction (concrete, bricks, tiles, and ceramics; LoW Section 17 01) constitutes the dominant waste stream in all regions studied, excluding soil. However, a significant data comparability issue arises from the reporting of "excavated soil and stones" (LoW-17 05 04). For example, data from Cyprus shows that excavated materials constitute a large proportion of the total waste stream (~1.83 million tons out of 2.39 million tons in 2023) and overshadow data on structural construction materials [4]. Similarly, Greece reports that "soil" constitutes 55.96% of non-hazardous waste [5, 6]. In contrast, Estonia reports a total of 2.5–3 million tons of waste, with mineral waste predominating, but emphasizes that the distinction between "waste" and "by-product" for soil is often based on immediate reuse potential, creating areas with statistical uncertainty [7]. In Slovenia, 8.5 million tons of CDW were generated in 2023 and 7.4 million tons were used for backfilling [8]. According to Eurostat statistics, 390,530 tons and 1,584,229 tons of CDW, of which 1,2% and 39.1% are excavated soil, were generated in Latvia and Romania, respectively, in 2018 [2]. The European Environment Agency reported that 82% of Switzerland's total waste volume came from construction and civil engineering activities [9]. In Türkiye, CDW statistics are not officially reported, so the breakdowns required for MP entries are unavailable. This statistical gap, alongside Greece's high backfilling share, directly blocks the baseline inventory that any digital MP requires, making it the first obstacle to a unified tracking system.

Among the EU countries examined, recycling rates for mineral CDW vary, with some Member States reporting figures below the EU average while maintaining overall recovery rates close to or above the 70% WFD target. This variation partly reflects differences in how Member States classify recovery operations following the 2018 revision of the Waste Framework Directive [2]. Despite around 95% of CDW being reported

as recycled in 2022 [2], in Switzerland, there is no segregated data reporting on CDW treatment, unlike in EU member countries, which makes comparisons difficult. On the other hand, there is no data available on CDW treatment in Türkiye, but backfilling is currently widely used and has been encouraged at the policy level for many years.

3.2 Data Granularity and Metadata Availability

When examining additional metadata collection criteria such as geographic location, building category, or material source -which are significant for the Material Passport concept beyond the basic waste codes of the countries under review- the responses revealed a lack of standardized data protocols necessary for functional Material Passports.

Estonia and Latvia are in the early stages of metadata collection. Currently, data collected on transported waste includes waste producer and recipient, waste type (EWC code), quantity (tonnage), and date of transfer. The focus is on the logistics chain, not on material characterization. However, in Estonia, some companies are developing more detailed digital tools as part of pre-demolition audits [10]. Basic information, such as coordinates, quantity, waste code, designation, and waste recipients, is collected on a mandatory basis in Switzerland, while material origin, geometry, description, various circular and environmental indicators can be collected voluntarily in line with the activities of various sector stakeholders. In Cyprus, the regulations in force require data collection at a very detailed level, demanding the collection and presentation of certain data that, in a sense, make circularity mandatory, such as projected recovery options and management methods. In Romania, no metadata is collected beyond the basic descriptive information required for reporting on CDW in EU member countries. This deficiency causes the material's history and potential contamination risks to be lost as soon as it leaves the site. In Türkiye, the absence of a central registration system worsens the situation; even basic geographic location data is often missing in uncontrolled dumping scenarios. In Slovenia, a digital platform for the Digital Product Passport has been introduced, enabling end-to-end traceability of materials from demolition to recycling and reuse. Metadata includes information such as waste producer, waste type (EWC code), status (hazardous, non-hazardous), transport, processing, treatment, treated mass, etc. [11].

3.3 CDW Separation and Processing Techniques

A comparative analysis of separation and processing technologies reveals a significant "technological divide" between practices in the countries under review. This difference significantly impacts the quality of secondary raw materials (SRM) and the efficiency of disaster waste management. In most of the countries studied (Estonia, Romania, Cyprus, Greece), the processing of CDW is characterized by standard mechanical process chains supported by predominantly manual separation [2, 7, 12]. The typical process involves separating large fractions, mechanical crushing with jaw or impact crushers, screening, and magnetic separation for ferrous metals. While the basic technology is similar, operational differences may exist among the countries. Slovenia emphasizes the use of mobile crushing units directly on construction sites, prioritizing logistical flexibility over advanced stationary processing. In Türkiye, field observations show that advanced

separation is often skipped in favour of rapid rubble removal, and heavy machinery is mostly used to extract high-value steel (rebar), while other potential resources are not recovered [13]. Switzerland exhibits a high level of industrial maturity and automation, based on sensor-based separation and the integration of Artificial Intelligence (AI). Additionally, wet mechanical processing (washing) is used to ensure the high purity of recycled aggregates. A critical finding is that most countries under consideration lack advanced quality-control technologies such as X-ray Fluorescence (XRF) and Hyperspectral Imaging (HSI); this stems primarily from the absence of standardised regulatory requirements rather than from capital cost alone, since such tools remain optional under current EoW regimes.

3.4 End-of-Waste (EoW) Status and Circular Economy Implementation

Most of the countries examined in this study operate at the lower levels of the waste hierarchy. The end-of-life process of CDW is largely limited to mechanical crushing for low-quality applications. In Estonia, Cyprus, Latvia, Greece, and Slovenia, the primary application of the 5Rs of Waste Management (Refuse, Reduce, Reuse, Repurpose, Recycle) principle involves the aggregate conversion of concrete and/or masonry materials to be used in road construction and/or as filler material in concrete blocks. Apart from copper scrap, metal, and glass cullet, there are no specific EoW criteria for other fractions of CDW as defined by the EU [14–16]. Switzerland is an exception, reporting that the active application of the reuse and recycling principles for mineral wastes to be utilized as aggregate is a standardized practice. In Türkiye, however, there is no specific national regulation defining waste classification criteria for materials obtained from CDW. This legal gap often leads to even uncontaminated, crushed concrete being legally considered waste, preventing the development of a secondary raw material market.

3.5 Disaster Waste Management Protocols

Analysis of country-specific data reveals a significant gap in the development of regulatory frameworks for disaster waste management. Several parameters, primarily the country's location, can change the scope of "disaster waste". In the case of disasters, the balance between rapid recovery and material circularity is critical. Most countries lack a separate legal definition or statistical category for disaster waste. In Switzerland, Estonia, Romania, and Cyprus, the waste generated by sudden building collapses or emergency demolitions is considered disaster waste and not recorded separately; instead, emergency plans are activated, and the resulting waste is included in general CDW streams [17]. In Türkiye, earthquakes are a serious reality, causing sudden, massive waste generation. Latvia has an active national disaster management system, but it lacks a dedicated disaster debris management plan comparable to those adopted in high-risk countries [18]. In contrast, Slovenia adopted the "Response Act" to prioritize disaster debris after the 2023 floods, marking a shift towards event-based legislation [19]. Greece prioritizes restoring access to infrastructure, often skipping detailed separation processes during disaster demolitions. This situation reflects conditions in Türkiye, where emergency demolitions and the urgency of debris removal have led to the mixing of hazardous and

non-hazardous waste, severely limiting the potential for high-value recycling and providing an example of how standard regulations in force are insufficient and may pose operational challenges.

4 Conclusion

This comparative analysis reveals that while most of the countries under investigation have aligned their legal frameworks with EU Circular Economy principles, a significant "operational gap" remains in technological infrastructure development and data generation (see Table 1).

On the one hand, Central European models (e.g., Switzerland) demonstrate that high-value circularity can be achieved by aligning strict End-of-Waste regulations with advanced automation. Conversely, the Balkans and Mediterranean regions (e.g., Turkey, Greece, Romania) face a technological readiness gap, in which reliance on manual sorting and visual inspection limits the potential to produce high-quality secondary raw materials. In countries like Turkey, the loss of material metadata during rapid demolition undermines the current post-disaster management approach, making it unsustainable. This gap becomes more critical when considering the implementation of Material Passports (MPs).

Based on the findings, several policy implications emerge: (i) national waste monitoring systems should evolve from tonnage tracking to quality metrics (metadata) tracking to support the creation of valid Material Passports, (ii) legal targets for recycling rates should be accompanied by incentives for improving sorting infrastructure with sensor-based technologies and (iii) for disaster-prone regions, it is proposed that the concept of Material Passports be separated from the demolition phase and integrated into the design and use phases as a preventive disaster management tool.

Ultimately, achieving a resilient circular economy requires a fundamental shift towards data-driven material characterization, enabling buildings to function as material banks even under post-disaster conditions.

Table 1. Summary of the current state of countries under consideration

Country	Data Availability	EoW Status and Circularity	Sorting & Processing Technologies	Disaster Response Protocol
Cyprus	Advanced metadata collected.	Circularity is limited to low-quality road backfilling.	Standard conventional facilities.	Crisis management through event-based Cabinet decisions.
Estonia	Early stages of metadata collection.	More than 90% of the material used was recovered.	Standard conventional facilities.	Framework of the general "Emergency Response Plan".
Greece	Collects only basic EU-required data.	Reports a high backfilling rate.	Basic mechanical processes.	Focuses on rapid infrastructure restoration.
Latvia	Early stages of metadata collection.	Circularity is limited to low-quality backfilling.	Basic mechanical processes.	Currently lacks an active disaster management plan.
Romania	Collects only basic EU-required data.	Recycling rates remain below the EU average.	Basic mechanical processes.	No separate legal definition for disaster waste.
Slovenia	Provides clear statistical breakdowns. DPP practice is available.	Landfill taxes encourage circularity.	Mobile processing units are common.	A special "Intervention Law" was enacted after the 2023 floods.
Switzerland	Integrated digital records and detailed statistics are available.	The EoW criteria are clear. Reusing concrete is standard practice.	AI-based robotic sorting, sensors, and wet processing.	The General Waste Management Act (VVEA) covers disaster situations.
Türkiye	CDW statistics are not reported.	No national regulation for waste classification.	Basic mechanical processes.	Massive waste scale causes bottlenecks.

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Urban Development as Circular Economy Business Incubator Enabled by Digitalisation

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Abstract. Circular economy business incubators can reposition real estate from static assets to venture platforms that generate, test, and scale circular business models in urban regeneration. This creates an opportunity to make adaptive reuse and urban development projects more innovative, productive, and financially viable. Yet many so-called circular economy hubs are still treated mainly as places where circular activities happen, not as operating models that turn circular intent into replicable ventures and feasible business outcomes. This study asks how adaptive reuse and urban development projects can be configured as circular economy incubators, and what role digitalisation plays in that process. Using a synthesized taxonomy of 40 circular economy business model archetypes, the study compares three European real estate hubs selected for their contrasting governance models, scales, and explicit incubator or accelerator design. The results identify three incubator configurations: curated industrial symbiosis within a single asset; circular construction coworking combined with a no-equity incubator centred on partnerships and procurement pilots; and a public-private eco-industrial park with specialist labs that bridge lab-to-pilot scaling. Across all three, digitalisation emerges as a key enabler of value creation because it makes circular flows visible, traceable, and manageable. AI-enabled Building Information Models, digital twins, material passports, asset databases, and reuse-matching platforms function as trust infrastructure for tracking, verifying, and coordinating these flows. The study contribution is a scalable "urban circular economy venture project" model that reframes real estate as a venture platform for circular innovation.

Keywords: business model incubator · urban regeneration · digital twins · urban circular venture project · smart cities · entrepreneurship

1 Introduction

The built environment remains a structurally high-leverage domain for circular economy transition because it concentrates (i) material inventories, (ii) capital expenditure cycles, and (iii) governance decisions at points of (re)development - while still accounting for

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one-third of global energy use and CO_2 emissions [1, 2]. Against this backdrop, "circular economy hubs" have proliferated, yet practice and academia often treat them as places with circular activities rather than as operating models that convert circular intent into replicable and financially feasible venture outcomes [5, 6].

The research questions guiding this study are: *How can adaptive reuse or newly developed real estate assets be configured as circular economy incubators - i.e., venture platforms that generate, test, and scale circular business models - and Which role does digitalisation play?*

For urban studies, the question targets "places" and governance - how urban regeneration become a venture that coordinate multi-actor experimentation and diffusion (living labs) rather than isolated projects. For entrepreneurship research, it targets incubation configurations and business model innovation: the incubator is treated as a structured organisational process that shapes venture outcomes, not simply as co-working real estate [4–6].

2 Literature Review and Theoretical Foundations

2.1 Circular Economy Business Models: Definitions and Frameworks

Geissdoerfer et al. (2020) define a circular business model (CBM) as "a business model in which the conceptual logic for value creation is based on utilising economic value retained in products after use in the production of new offerings". This definition extends the classic business model canvas of Osterwalder and Pigneur (2010), which describes business models through value proposition, value creation and delivery, and value capture. Lewandowski subsequently expanded the canvas to include "take-back systems" and "adoption factors" as additional circular business elements [7, 8].

Bocken et al. (2014) developed eight foundational sustainable business model archetypes: maximise material and energy efficiency; create value from waste; substitute with renewables and natural processes; deliver functionality rather than ownership; adopt a stewardship role; encourage sufficiency; re-purpose the business for society/environment; and develop scale-up solutions. These have been widely cited as a starting framework for CBM innovation. Bocken et al. (2016) further specified three resource strategies for circular models - narrowing, closing, and slowing resource loops - which, when combined with open and closed innovation strategies, yield six strategic approaches to CBM innovation [9, 10].

Antikainen and Valkokari (2016) built upon the canvas approach by adding ecosystem-level trends and drivers, stakeholder value considerations, and sustainability impact assessment, producing a Framework for Sustainable Circular Business Model Innovation. Their framework emphasises that systemic innovation, rather than incremental product-level changes, is needed to mainstream circularity [24].

2.2 Taxonomy of 40 Business Model Archetypes

By synthesising major taxonomies, this research compiles a consolidated set of 40 CBM archetypes. Lüdeke-Freund, Gold, and Bocken (2019) conducted a morphological analysis of 26 CEBMs from the literature, proposing six major patterns: repair and maintenance; reuse and redistribution; refurbishment and remanufacturing; recycling; cascading and repurposing; and organic feedstock [10]. From theory to practice, Pieroni, McAloone, and Pigosso (2020) systematised 20 archetypes arranged according to downstream/upstream architecture and value type - distinguishing between product-oriented and service-oriented models [26].

Hansen, Lüdeke-Freund, and Fichter (2020) proposed 22 actor-specific CBM patterns, each customisable according to three product-service system degrees (product-oriented, use-oriented, and result-oriented), generating 42 sub-patterns in total [25]. Drawing on Kirchherr, Reike, and Hekkert's (2017) 4R framework - reduce, reuse, remanufacture, recycle - these patterns span from "maintenance and upgrade" through to full material recovery [11, 12].

The Ellen MacArthur Foundation's "butterfly diagram" provides the overarching systems map, illustrating the continuous flow of materials through technical and biological cycles and the value retained at each loop - from sharing and maintaining (inner loops) to recycling (outer loop). For the built environment specifically, Arup and the Ellen MacArthur Foundation, in collaboration with RICS, identified five circular real estate business models: flexible spaces, adaptable assets, relocatable buildings, residual value recovery, and performance procurement [27].

Drawing on Bocken et al.'s eight archetypes, Lüdeke-Freund et al.'s six major patterns and 26 sub-models, Hansen et al.'s 22 actor-specific patterns, Pieroni et al.'s 20 systematised archetypes, and five real estate specific models, this study consolidates existing taxonomies into approximately 40 distinct CBM archetypes after removing overlaps and duplicates. These archetypes serve as the analytical lens for the case studies presented here. Their detailed conceptual development is beyond the scope of this paper and will be addressed in a separate publication. Relevant groundwork on the multi-scalarity of CBM and archetypes has been carried out by the main author, Meslec (2025) [30, 31], within the CircularB COST Action and the Circular Approaches in the Built Environment (CABE) Driving Urban Transitions EU project.

2.3 Digitalisation and AI as Enabler

Liu et al. (2022) introduced a framework showing how digital tools such as the Internet of Things and Big Data enable circular economy practices [28]. They explain how functions such as data collection support mechanisms like product tracking and process optimization, which reduce industrial waste. Data-driven business models enabled by digital technologies - including servitisation, product-as-a-service, the sharing economy, and product life extension - are reshaping CE implementation [13–15]. Advances in AI are likely to accelerate these models by improving prediction, coordination, and decision-making across circular systems.

In the Smart City context, Building Information Modelling (BIM) and Digital Twins are enabling technologies. BIM supports the planning and management of materials

across the lifecycle of a building, while material passports, digital documents containing information on products, components, and materials, provide a basis for circular decision-making. The BIM-based Building Circularity Passport, developed by EPEA GmbH and Die Werkbank IT, supports real-time sustainability assessment at the design stage, allowing planners to analyse CO_2 footprints, recyclability, and residual values of building materials in seconds [13, 15, 17]. AI development may turn these tools into more adaptive systems that simulate circular outcomes and optimize in real time.

Blockchain and Internet of Things (IoT) complement BIM by enabling material traceability across the lifecycle. Hunhevicz and De Wolf (2023) proposed six blockchain applications for a circular digital built environment, including supply chain traceability and material ownership tracking [29]. Research at Monash University also demonstrated a BIM-blockchain solution that allows construction practitioners to share building component information on an immutable medium, supports circular design through collaboration, and facilitates a bank of reusable BIM families [13–15]. Looking forward, radical change driven by AI may connect blockchain, IoT, and BIM into integrated systems that verify materials, predict reuse potential, and coordinate actors across the building lifecycle.

3 Methodology

This study employs a qualitative research design combining two methods. First, a literature review synthesis draws on the foundational CE business model frameworks discussed above, consolidating approximately 40 distinct business model archetypes from five major taxonomic studies.

This study uses comparative case study analysis. Three cases were selected based on (i) real-estate grounding, (ii) explicitly positioned as incubators/accelerators or host such programmes, (iii) high-visibility and documented in official sources, and (iv) structurally diverse across governance and spatial scale. The selection assumes that "incubation" can be initiated either as (a) a building-based tenant ecosystem (BlueCity), (b) an incubator programme embedded in a circular building and co-working ecosystem (Impact Hub Berlin at CRCLR House), or (c) embedded specialist incubation infrastructure inside a larger eco-industrial real-estate development (Blue Gate Antwerp via BlueChem/BlueApp) [18, 20, 22].

4 Comparative Case Results

As revealed by the comparison in Table 1, BlueCity is repeatedly described as a circular incubator in a repurposed former swimming complex, operationalising industrial symbiosis ("output of one is input for another") as the core coordination mechanism. Impact Hub Berlin at CRCLR House anchors incubation within a circular-construction demonstrator: it combines co-working, maker spaces and events with a structured incubator programme (Circular Together) that funds founders via stipends and explicitly prioritises partnership formation without taking equity - i.e., incubation is a designed governance/contracting function, not a by-product of tenancy. Blue Gate Antwerp positions a remediated brownfield as an "eco-effective, water-bound" business park - explicitly

a public-private project - offering collective utilities and hosting specialist incubators (BlueChem, BlueApp) that target lab-to-pilot scaling in sustainable chemistry/materials [18, 20, 22].

Table 1. Comparison Circular Economy Business Incubators

Dim.	BlueCity	Impact Hub Berlin (CRCLR House)	Blue Gate Antwerp (BlueChem/BlueApp)
Governance	Curated accelerator.	Public programme:	PPP vehicle.
Incubation & business model	Workspace and production/offices plus lab spaces; fast-track incubator programmes and public programming; business model includes workspace/event rental and programme platforming.	Incubation is programme-based: 6-month with coaching, mentoring, pilot support; stipends (€2,000/month) and "no equity"; co-working membership and events as complementary revenue/community layer.	Business park real estate development (phased) reserved for firms pursuing "linear growth through circular operations"; embedded incubators provide labs, offices, pilot infrastructure and advisory services.
Spatial programme	Adaptive reuse; co-location.	Reused warehouse; maker/events.	63 ha park; utilities.
Financing strategy	Private/ongoing.	Space revenues and public funding.	PPP remediation; plots/leases.
Digitalisation tools	Reuse mapping.	Material/product passports.	Asset database; BIM KPIs.
Metrics (reported)	12,000 m^2; 30+ ventures.	3,500 m^2; material claims.	Job target; remediation/KPIs.
Constraints	Capital intensity; retrofit risk.	Verification; procurement routes.	Phasing cost; governance complexity.

4.1 Derived Archetypes and Venture Lessons

Three archetypes emerge: (i) single-asset symbiosis incubator - co-location plus tenant curation enabling industrial symbiosis. (ii) circular-construction coworking and programme incubator - partnership brokerage and procurement pilots drive scaling. (iii) PPP eco-industrial park with specialist incubators. Digitalisation functions as the hub's trust infrastructure [18, 20, 22].

A cross-cutting implication is that digitalisation must be treated as the hub's "infrastructure" and enabler. The cases show early components (material passports; BIM-tracked asset databases; re-use marketplaces), with no clear AI implementation, while

EU policy indicates these data infrastructures are becoming normalised through digital building logbooks and digital product passports, lowering institutional barriers to replication [13, 15, 17].

4.2 Circular Economy Incubator Design Principles

Cross-case, the "urban circular economy venture" model comprises five principles: adaptive real-estate platform (modular reconfiguration), embedded circular intelligence (BIM-based circularity/material passports), symbiotic tenant curation (flow complementarity), accelerator programming (mentoring; procurement pilots), digital twin integration (monitoring; scenario planning) [1, 9, 13]. However, the digital twin integration is the enabler of the circular economy ventures through:

- Data layer (material passports and BIM)
- Tracking layer (IoT and blockchain): IoT-enabled monitoring of energy, water, and material flows
- Platform layer (digital marketplaces and matching)

These digital layers align with the critical digital functions identified by Liu et al. [28], particularly tracking and tracing, monitoring, optimising, and matching. The finding that digitalised firms are more likely to adopt CBM is confirmed at the building scale: projects that deploy digital material passports, BIM-based lifecycle tools, and IoT monitoring systems are demonstrably more effective at hosting multiple CBM simultaneously [13–15].

5 Conclusion and Limitations

This paper has demonstrated that circular economy business incubators can reposition real estate from static assets to dynamic venture platforms that generate, test, and scale circular business models within urban regeneration contexts. Developers and real estate investors can treat circularity as a venture-portfolio logic rather than a compliance cost.

The proposed "urban circular venture project" model introduces five design principles: adaptive real estate platforms, embedded material intelligence, symbiotic tenant curation, circular accelerator programming, and digital twin AI integration. Future research should test replicability of these models and empirically test the design principles through longitudinal studies of newly established circular incubators and quantify the long-term economic value generated by digitally enabled CBM at the urban scale. The transition from linear to circular real estate represents not merely an environmental imperative but a significant business model innovation opportunity enabled by digitalization and AI; one in which buildings themselves become the laboratories of the circular economy.

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Improving Municipal Waste Management in Librazhd, Albania: A Cost–Benefit Analysis

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Abstract. This paper explores opportunities for economic and environmental improvement in the waste management system of the Municipality of Librazhd, with a particular focus on plastic waste. It assesses how improved source separation in households, institutions, and businesses could reduce municipal disposal expenses while generating income from recyclable materials. The study describes the current state of waste management and identifies key stakeholders involved in collection, sorting, and recycling by reviewing Librazhd's waste management plans. It examines the composition of collected waste, the contributions of public and private entities, and existing recycling rates. Additionally, the research evaluates the economic benefits of improved waste separation, including reduced landfill and cleanup costs, as well as the revenue potential from selling sorted plastics to local recyclers rather than incinerating them. Drawing on interviews with representatives of recycling companies and municipal waste managers, it also explores market dynamics for recyclable plastics. A cost–benefit analysis is used to assess the financial advantages, cost savings, and broader implications of transitioning to a more sustainable, circular approach to plastic waste management. The primary objective is to recommend practical, affordable solutions tailored to Librazhd's local context, thereby enhancing the efficiency and environmental performance of the municipality's waste management strategy. The findings are intended to support policymakers in making evidence-based decisions and fostering collaboration among stakeholders to improve regional waste management performance.

Keywords: Plastic Waste · Municipal Waste Management System · Circular Economy · Librazhd Municipality, Albania

1 Introduction

Municipal waste management continues to present environmental and governance challenges across many Albanian municipalities, including Librazhd. Increasing waste generation, limited recycling participation, aging infrastructure, and the distance to landfill facilities place pressure on the local waste management system. Plastic waste is particularly problematic due to its persistence in the environment and the limited capacity for effective collection and recycling.

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This study examines current waste management practices in Librazhd with a focus on recyclable waste and the potential for improving separation at the source. It explores whether a shift toward a more recycling-oriented system could provide environmental and economic benefits, particularly through improved infrastructure and stronger coordination among stakeholders. The study applies a mixed-methods approach to evaluate the feasibility of introducing a simplified two-bin waste separation system. The remainder of the paper is organized as follows. The next section outlines the conceptual background related to waste management and circular economy approaches. This is followed by the presentation of research design and empirical findings. The final section discusses policy implications and offers recommendations for improving municipal waste management in Librazhd.

2 Study Context and Conceptual Background

Municipal waste management remains a persistent challenge in many small and medium-sized municipalities, particularly in transition economies where infrastructure, financial resources, and institutional capacity are often limited [1, 2]. In such contexts, waste systems tend to rely heavily on collection and disposal, with limited development of recycling and material recovery practices.

In response, circular economy approaches have gained attention as a more sustainable alternative to traditional waste management models. By promoting reduction, reuse, recycling, and recovery, these approaches aim to extend material life cycles and reduce dependence on primary resources [3–5].

Plastic waste represents a particularly critical issue within this transition. Due to its durability and slow degradation, plastic accumulates in landfills and natural environments, contributing to long-term ecological risks such as microplastic pollution [6–8]. Where waste separation systems are absent or underdeveloped, plastic is typically disposed of together with mixed waste, reducing opportunities for recovery and increasing environmental impacts.

From an economic perspective, improved waste separation can also generate measurable benefits. Studies show that recycling systems can reduce landfill costs, lower environmental remediation expenses, and create value through material recovery [4, 9]. However, in many transition economies, including Albania, structural constraints such as limited infrastructure, low public participation, and weak institutional coordination continue to limit the effectiveness of recycling systems [2, 10, 11].

Within this broader context, the Municipality of Librazhd represents a relevant case for examining practical improvements in waste management. Located in central Albania within the Elbasan district, Librazhd has a population of approximately 10,990 residents [11]. As in many small municipalities, waste management operates under conditions of limited infrastructure and uneven terrain. Collection services function relatively well in the urban core, where access allows for regular service provision and acceptable levels of cleanliness. At the same time, residents display environmentally favorable practices, such as reusing plastic materials and relying on local water sources, which could support future recycling initiatives [11].

Despite these positive aspects, waste management in Librazhd continues to follow a largely linear model in which waste is collected and transported to the regional landfill, without formal systems for source separation or recycling. While proximity to the Elbasan landfill simplifies disposal logistics, it also reinforces dependence on landfilling rather than encouraging material recovery [11, 12]. Outside the urban center, service provision becomes more limited due to dispersed settlements and difficult terrain, leading in some cases to informal disposal practices, including dumping waste in undesignated areas or into the Shkumbin River [11]. Similar patterns observed in other rural areas with limited infrastructure contribute to environmental degradation and waste leakage [13, 14].

These combined conditions make Librazhd a useful case for exploring realistic pathways toward improved waste management in smaller municipalities. Its relatively small population, existing environmental awareness, and logistical characteristics provide a basis for change, while persistent service gaps and reliance on landfill disposal highlight the need for more structured approaches. This study therefore evaluates the feasibility of introducing a simplified two-stream waste separation system as a practical step toward applying circular economy principles in a small-municipality context.

3 Research Design and Methods

This study uses a mixed-methods approach to evaluate the feasibility of introducing a recyclable waste management system in the Municipality of Librazhd. The quantitative analysis evaluates the economic feasibility of shifting from the current mixed-waste collection system to a two-stream waste separation model. Data were obtained from the Librazhd Municipal Waste Management Plan, including information on waste composition, recyclable volumes, and operational cost parameters. A simplified cost–benefit analysis (CBA) was applied to estimate the costs and potential economic returns of the proposed system. Transition costs include capital expenditures for infrastructure improvements and operational expenditures related to the collection, transport, and processing of separated waste streams. All values are expressed in Albanian Lek (ALL) and adjusted for inflation.

Economic benefits were estimated using a model adapted from previous research by the author and adjusted to Librazhd's waste volumes, population size, and expected recycling rates [12]. The analysis includes revenues from recyclable materials, energy savings from recycling processes, avoided landfill costs, and value generated through material recovery. Financial feasibility was assessed through Net Present Value (NPV) and the Benefit–Cost Ratio (BCR) over a five-year evaluation period.

The qualitative component explores institutional and operational factors affecting waste management practices in Librazhd. A total of 6 semi-structured interviews were conducted with municipal representatives of Librazhd, representatives from recycling organizations, and actors from the general public involved in recycling activities. These discussions provided insights into infrastructure limitations, coordination challenges, and current waste management practices.

4 Economic Feasibility Analysis of the Two-Stream Waste System

Librazhd currently relies on a mixed-waste collection system in which recyclable materials are not systematically separated from general waste. As a result, potentially valuable materials are often disposed of through landfill or incineration. This section evaluates whether introducing a simplified two-stream collection system, separating organic waste from recyclable materials, could represent a financially viable alternative for the municipality.

The analysis uses data from the Librazhd Municipal Waste Management Plan, including waste composition, annual waste volumes, and operational cost parameters. A five-year time frame (2025–2030) was selected in order to reflect both the initial investments required for system implementation and the operational adjustments expected during the early stages of the program. All monetary values are expressed in Albanian Lek (ALL) and adjusted using an assumed annual inflation rate of 2.5%.

Recyclable materials such as paper, plastic, glass, and metal represent a significant share of Librazhd's municipal waste stream. Together these fractions account for approximately 36.6% of recyclable waste, corresponding to an estimated 561 tons annually. Under the current system, most of these materials are collected as mixed waste and transported to landfill facilities, generating disposal costs without creating economic value through material recovery. Over the five-year assessment period, the estimated cost of implementing the transition amounts to 6,782,000 ALL, combining both capital and operational expenditures (Table 2).

Table 2. Transition Costs for Librazhd

Category	% Waste	Tons/Year	Capex (ALL)	Opex (ALL)	Total (ALL)
Paper	13.8%	211	511,200	2,044,800	2,556,000
Plastic	15.4%	236	571,200	2,284,800	2,856,000
Glass	4.2%	64	155,200	620,800	776,000
Metal	3.2%	49	118,800	475,200	594,000
Total	36.6%	561	1,356,400	5,425,600	6,782,000

Note: CapEx includes one-time infrastructure costs such as bins and site adjustments, while OpEx represents recurring costs for collection, transport, and processing of separated materials.

Potential economic gains were estimated using a benefit-transfer framework derived from the model proposed by Zaman (2016) [4], adjusted to reflect Albania's waste composition and recycling conditions. The assessment includes revenues from recyclable materials, energy savings associated with recycling processes, avoided landfill expenditures, and additional value generated through material recovery. These parameters were calibrated using findings from previous research conducted by the author on municipal waste management systems [12] and adapted to Librazhd's population size, waste volumes, and expected recovery rates. After applying a 3% discount rate, the estimated total benefits generated during the five-year period amount to 86,606,652.12 ALL.

To evaluate the financial performance of the proposed system, two commonly applied indicators were used: Net Present Value (NPV) and the Benefit–Cost Ratio (BCR). The NPV was calculated using the following expression:

$$NPV = \sum_{t=0}^{n} \frac{B_t - C_t}{\left(1 + r\right)^t}$$

where B_t represents benefits in year t, C_t represents costs, r denotes the discount rate (3%), and t refers to the year within the evaluation period (2025–2030).

The Benefit–Cost Ratio (BCR) was estimated as

$$BCR = \frac{NPV_{benefits}}{NPV_{costs}}$$

The calculated indicators were then used to assess the overall economic performance of the proposed waste separation system (Table 3).

Table 3. Transition Viability for Librazhd

Metric	Librazhd
Total Transition Cost (ALL)	6,782,000
Total Benefits (ALL)	86,606,652.12
NPV	79,824,652.12
Viability	Economically Viable

The results indicate that the projected economic gains significantly exceed the estimated implementation costs. Although municipalities with larger waste volumes may generate higher absolute returns, the findings suggest that similar waste separation systems can also produce positive economic outcomes in smaller municipalities such as Librazhd. Future variations in recycling market prices, infrastructure costs, or regulatory conditions could, however, influence the long-term performance of the system.

5 Operational Barriers to Waste Separation

Survey and interview data from municipal officials, private-sector representatives, and residents identify several factors shaping plastic and recyclable waste management in Librazhd. Together, these factors affect the municipality's ability to move beyond a landfill-based system toward more circular waste management practices.

Interviews reveal differences in environmental awareness across demographic groups. Younger residents tend to be more familiar with recycling concepts due to environmental education initiatives, whereas older residents often require additional guidance. Although many respondents expressed willingness to separate waste, participation remains limited because of inadequate infrastructure and irregular collection services.

Infrastructure deficiencies were repeatedly mentioned by respondents. Peripheral areas often lack sufficient waste containers, and some existing bins are damaged or poorly maintained, contributing to illegal dumping and dissatisfaction with municipal services. Limited collection coverage in remote settlements further aggravates these challenges. Residents also suggested practical measures to reduce plastic waste, such as installing public drinking fountains to encourage the use of refillable bottles.

Institutional factors also influence system performance. The municipality is currently developing a waste management plan for 2025–2030 that proposes a simplified two-stream separation system for organic and recyclable waste. However, municipal representatives noted that implementation may be constrained by limited financial resources, fragmented administrative responsibilities, and weak enforcement mechanisms.

Stakeholders from the recycling sector emphasized that effective source separation is essential for improving recycling efficiency. According to these respondents, recycling facilities frequently operate below capacity because properly separated materials are not consistently available. A simplified two-bin system was therefore considered a practical approach for municipalities with limited infrastructure such as Librazhd.

Table 1 summarizes the main challenges identified and outlines potential policy responses that could support the municipality's transition toward improved waste management practices.

Table 1. Policy Implications Matrix for Improving Waste Management in Librazhd

Key Challenge (Impact)	Policy Implications for Circular Waste Management
Insufficient or damaged bins in peripheral areas, resulting in illegal dumping and poor public cleanliness	Replace damaged bins and expand coverage to enable source separation
Low awareness of waste separation, particularly among older residents, leading to low recycling rates and contamination	Implement targeted awareness campaigns and community outreach
High consumption of single-use plastic bottles, increasing household plastic waste	Install public drinking fountains and promote refillable bottle use
Weak monitoring and enforcement of illegal dumping, contributing to persistent litter hotspots	Strengthen inspections, penalties, and citizen reporting mechanisms
Limited waste collection coverage in remote areas, causing waste accumulation and environmental risks	Extend collection routes and establish shared rural collection points
Lack of incentives for recycling, resulting in recyclable materials being disposed of with mixed waste	Introduce small financial incentives or buy-back schemes
Limited communication of municipal waste policies, creating public skepticism and low participation	Publish clear policy summaries and organize community consultations

6 Conclusions and Policy Directions

The findings of this study indicate that introducing a simplified waste separation system in Librazhd could offer both economic and environmental advantages for the municipality. The CBA produced a strongly positive NPV of 79.8 million ALL, while estimated benefits (86.6 million ALL) considerably exceed the projected transition costs (6.78 million ALL) over the five-year assessment period. These results suggest that recovering recyclable materials rather than disposing of them through landfill can generate measurable financial returns while reducing environmental pressures.

Interviews revealed that current limitations include insufficient container infrastructure, low levels of waste separation, and uneven participation among residents. At the same time, many respondents expressed a willingness to engage in recycling activities provided that collection services are reliable and supported by clear guidance and incentives. Representatives from recycling companies also confirmed that local processing capacity exists for properly separated materials.

For Librazhd Municipality, gradual implementation of a two-stream collection system appears to be a realistic policy direction. Initial efforts should focus on expanding container infrastructure, improving collection coverage, and strengthening communication with residents regarding waste separation practices. Public awareness initiatives and small incentive mechanisms could further support household participation. In parallel, closer collaboration with private recycling operators and the inclusion of informal collectors could help improve material recovery and overall system performance.

In summary, the case of Librazhd illustrates that even municipalities with relatively small waste volumes can benefit from introducing basic recycling systems. Targeted infrastructure improvements combined with stronger stakeholder coordination may enable local governments to reduce landfill reliance while improving the economic efficiency of municipal waste management.

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Integration of Social Vulnerability for Seismic Risk Assessment of Greece

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Abstract. This research builds on the Social Vulnerability Index (SoVI) framework to evaluate the multiple dimensions of social vulnerability in Greece, integrating data on demographic structure, socio-economic conditions, institutional performance and service availability derived from census. Tourism is also explicitly incorporated among the vulnerability indicators, recognizing that tourists represent one of the most vulnerable population groups due to their limited knowledge of local conditions and possible lack of awareness of natural hazards. A dedicated weighting strategy is introduced within the SoVI computation to address differences arising from heterogeneous data availability as well as from variations in indicator significance. The resulting SoVI values reveal marked spatial variability in social vulnerability across the country and highlight the distinct ways vulnerability manifests under different regional and socio-economic conditions. The computed SoVI indices are subsequently combined with a seismic hazard map to produce a spatially explicit representation of integrated seismic risk, allowing the identification of the most vulnerable areas at national scale. Overall, the study provides an innovative interpretation of seismic risk in Greece by integrating social, economic, environmental, and exposure-related dimensions. The proposed framework directly supports resilience planning and sustainable urban governance, providing a transferable tool for evidence-based risk mitigation that can inform both regular and emergency land-use policies within the broader agenda of building a more resilient and sustainable built environment.

Keywords: Social Vulnerability · Risk Assessment · Resilience

1 Introduction

Earthquakes remain one of the most critical natural hazards affecting Greece, a country located in one of the most seismically active regions of Europe. While seismic hazard has been extensively studied, disaster impacts are not determined solely by ground motion intensity but also by the vulnerability of exposed populations [1]. In this context, social vulnerability plays a key role in shaping the ability of communities to anticipate, respond to, and recover from seismic events.

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Social vulnerability reflects the socio-demographic, economic, and institutional characteristics that influence disaster resilience. Previous studies [2–5] have demonstrated that populations with limited access to resources, lower income, reduced institutional support, or disadvantaged demographic profiles tend to experience disproportionately higher impacts during disasters. Understanding this dimension is therefore a prerequisite for designing sustainable risk reduction strategies and, more broadly, for transitioning toward built environments that are adaptive, inclusive, and regenerative.

The Social Vulnerability Index (SoVI), originally proposed by Cutter et al. (2003) [2], provides a robust framework to quantify these dimensions through composite indicators. Despite its relevance, the integration of social vulnerability into seismic risk assessment in Greece remains limited.

This study aims to address these gaps by developing a comprehensive assessment of social vulnerability at the regional (periphery) scale in Greece and integrating it with seismic hazard information through a risk matrix approach. Specifically, it develops a Social Vulnerability Index (SoVI) at the regional level, incorporates tourism as a key vulnerability factor, and integrates SoVI with seismic hazard to assess spatial patterns of social seismic risk. The social seismic risk framework developed here contributes to the sustainability and resilience agenda outlined in emerging European directives and research initiatives, including the circular economy approach to urban planning, which increasingly recognizes that social equity and hazard exposure cannot be decoupled from environmental and material sustainability.

2 Methodology

The methodology adopted in this study is based on the Social Vulnerability Index (SoVI). SoVI is constructed through the aggregation of multiple indicators, each representing a specific dimension of social vulnerability.

The selection of indicators is guided by both theoretical relevance and data availability. The adopted framework includes, as reported in Table 1, seven thematic groups representing the main dimensions of social vulnerability, namely population, education, economy, health, infrastructure, habitat, and governance.

In addition to the traditional SoVI indicators, this study explicitly incorporates a tourism-related indicator. Tourism is treated as a critical dimension of vulnerability due to the transient nature of tourist populations, their limited familiarity with local environments, and their potential lack of awareness of hazard-related risks. In regions characterized by high seasonal influxes, the presence of tourists can significantly alter exposure patterns and place additional pressure on local infrastructure and emergency systems. Each indicator, as reported in Table 1, may have either positive or negative cardinality, meaning it can increase or decrease vulnerability. In addition, given the heterogeneity of the selected indicators, a normalization procedure is required to ensure comparability across variables expressed in different units.

To obtain the values for the selected indicators, the raw national census data were therefore collected, standardized, and transformed into comparable scales according to

Table 1. Group and Indicators for the computation of SoVI along with their Cardinality.

No	Group	No	Indicator	Cardinality
1	*Population*	1	% Population < 18/19 years	+
		2	% Population > 60 years	+
		3	% Female	+
		4	% Disabled	+
		5	% Population of foreign nationality	+
		6	# Arrivals of non residents	+
2	*Education*	7	% Illiterate	+
		8	% Population without elementary education	+
		9	% Population without high school education	+
		10	% Population with high school degree	−
		11	% Population with university degree	−
3	*Economy*	12	Unemployment rate	+
		13	% Labor force working in secondary sector employment	+
		14	% Labor force employed in service industries	+
		15	% Female labor force participation	+
		16	Average income	−
		17	% [Fow poverty line	+
4	*Health*	18	# Hospitals	−
		19	# Beds	−
		20	# Doctors	−
		21	Crude birth rate	+
		22	Crude death rate	−
		23	Life expectance	−
5	*Infrastructure*	24	Service coverage index	+
		25	Road network (km/km^2)	−
		26	% House without water	+
		27	% House without electricity	+
		28	% Vehicles	−
6	*Habitat*	29	% Female headed households	+
		30	Population density (# people/ km^2)	+
		31	Housing density (# people /house)	+
		32	Urban density (# buildings/ km^2)	+

(*continued*)

Table 1. (*continued*)

No	Group	No	Indicator	Cardinality
		33	% House owners	–
		35	% Rural buildings	–
7	*Governance*	36	Crime rate	+
		37	Abstention rate from election	+

the min–max normalization procedure [3] expressed in the following equation:

$$X_{q,i} = \frac{x_{q,i} - \min_i(x_q)}{\max_i(x_q) - \min_i(x_q)} \tag{1}$$

where $x_{q,i}$ represents the value of indicator q for region i, and $\min_i(x_q)$ and $\max_i(x_q)$ are the minimum and maximum values of the same indicator across all regions and $X^N_{q,i}$ is the normalized index score of indicator q for region i.

The vulnerability score (V_i) for each spatial unit i was obtained by aggregating the normalized values of each indicator q, applying their corresponding weights, and rescaling the results to a range between 0 and 5 (S), where 0 represents the least vulnerable and 5 the most vulnerable conditions, according to the following equation:

$$V_i = S \sum_{q=1}^{n} w_q X_{q,i} \tag{2}$$

To improve the robustness and representativeness of the index, weights w_q were assigned to each indicator q according to two main criteria:

- Importance of the data, reflecting the theoretical relevance of each indicator to social vulnerability $w_{q,I.}$
- Quality of the data, capturing the reliability, completeness, and spatial resolution of the available information. $w_{q,Q}$

These weighting criteria ensure that variables with higher conceptual importance and better data quality exert proportionally greater influence on the final SoVI score. The final weight w_q assigned to each indicator, q, is computed by combining the weights for importance, $w_{q,I}$ and quality of data $w_{q,Q}$, applying the following equation:

$$w_q = \frac{w_{q,I} \cdot w_{q,Q}}{\sum_{q=1}^{n} \left(w_{q,I} \cdot w_{q,Q}\right)} \tag{3}$$

The composite SoVI value was obtained by aggregating the weighted vulnerability scores across all relevant thematic dimensions, producing an additive index that represents the overall social vulnerability of each region.

3 Social Vulnerability Assessment for Greece

The study focuses on the entire territory of Greece, analysed at the level of its thirteen administrative regions. The country presents a diverse geographical and socio-economic landscape, including densely populated metropolitan areas such as Attica, predominantly rural and mountainous regions such as Epirus and Western Greece, and insular regions characterized by strong seasonal variability, including the Aegean islands and Crete. This diversity results in pronounced differences in population structure, economic activity, infrastructure distribution, and access to services, all of which contribute to shaping the spatial patterns of social vulnerability. All data used in the analysis are derived from official sources, primarily the Hellenic Statistical Authority (ELSTAT) [6], complemented by national databases and open-access geospatial platforms.

The computed SoVI values highlight a clear spatial variability in social vulnerability across the Greek regions (Fig. 1). Higher vulnerability levels are observed in regions such as North Aegean and Western Greece, which are typically characterized by structural socio-economic challenges, including vulnerable populations, and more limited access to services. In contrast, metropolitan and economically stronger regions, such as Attica, where the capital Athens is located, and Central Macedonia, the region of the second largest city in Greece (Thessaloniki), display comparatively lower vulnerability scores, reflecting better infrastructure and more favourable socio-economic conditions. The results also underline the role of tourism as a relevant vulnerability factor, particularly in insular and coastal areas. In these regions, seasonal population fluctuations can place additional pressure on local resources and services, potentially increasing vulnerability during peak periods.

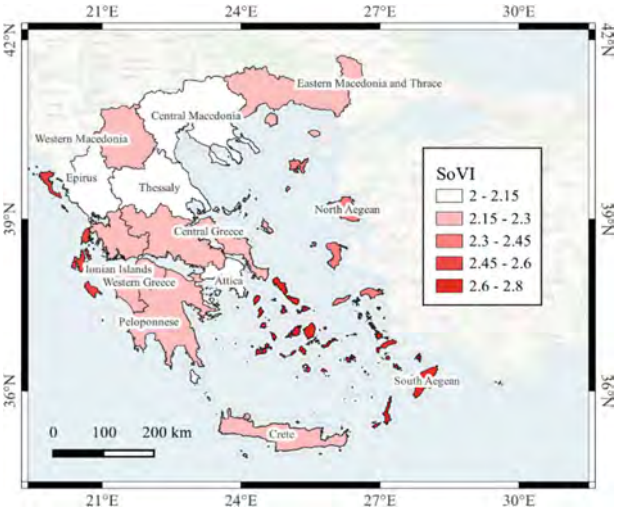


Fig. 1. Spatial distribution of SoVI in the 13 Greek regions.

To better understand the differences in SoVI across Greek Regions, a comparative analysis at the level of thematic indicators is carried out between Attica, representing

one of the least vulnerable regions, and the South Aegean, which exhibits the highest social vulnerability levels (Fig. 2).

The most pronounced difference emerges in the education indicator, where Attica shows significantly lower vulnerability. This can be attributed to the strong concentration of higher education institutions, including universities, in the Athens metropolitan area. Similarly, the health dimension highlights substantial differences, with Attica benefiting from a dense network of hospitals and healthcare facilities, while the South Aegean faces more limited access to such services due to its insular nature. In contrast, Attica exhibits higher vulnerability in the habitat dimension, likely reflecting urban challenges such as higher population density and crime rates typical of a capital city. Regarding population-related vulnerability, both regions show relatively high values, although driven by different factors: in Attica, this is linked to urban concentration and the presence of foreign populations, while in the South Aegean it is strongly influenced by seasonal tourism dynamics. Finally, the South Aegean Region shows higher vulnerability in infrastructure, which can limit service accessibility and institutional capacity. In terms of governance-related vulnerability, Attica exhibits a significantly higher crime rate than the islands, consistent with its characteristics as a metropolitan area. Overall, this comparison highlights how different socio-economic and territorial conditions shape vulnerability patterns across regions.

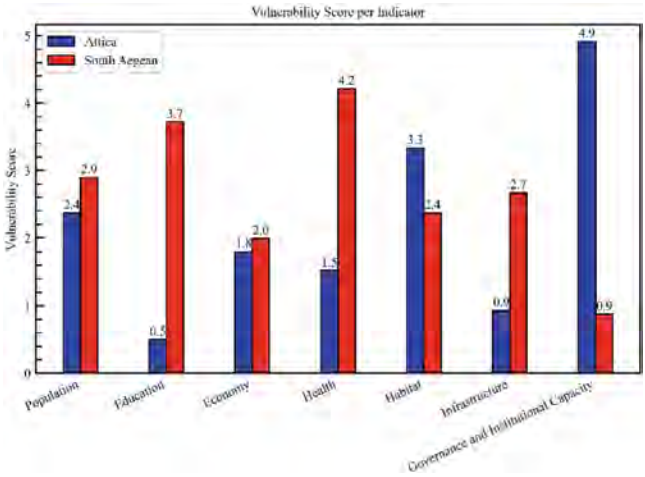


Fig. 2. Comparison of Vulnerability score for group indicator for two Greek regions, namely Attica and South Aegean, represented with red and blue bars respectively.

From a resilience perspective, these results suggest that regions with high vulnerability in education, health, and infrastructure face compounded disadvantages in their capacity to prepare for, absorb, and recover from seismic events. Identifying these structural deficits is a first step toward targeted investments in resilience-building measures, such as improving healthcare accessibility in island regions, strengthening social services in rural areas, and integrating vulnerability-aware land-use planning into sustainability frameworks at the regional level.

4 Integration with Seismic Hazard

One of the main applications of the SoVI map is its integration with seismic hazard to derive social seismic risk, namely SoVI risk. This framework allows areas characterized by similar hazard levels to be differentiated based on their socio-economic and demographic conditions, highlighting the role of social vulnerability in shaping overall risk.

In this study, seismic hazard is expressed in terms of peak ground acceleration (PGA) associated with a 475-year return period, derived from probabilistic seismic hazard analysis based on the European Seismic Hazard Model (ESHM20) [7]. To better capture spatial variability, hazard is evaluated at the municipality level.

The integration of social vulnerability with seismic hazard follows a matrix-based approach, commonly adopted in multi-hazard risk assessments [4, 5]. Both the SoVI score and the seismic hazard intensity (Fig. 3a) are independently classified into five ordinal classes, from 1 (very low) to 5 (very high). The combined social seismic risk index *(SoVI Risk)* for each municipality i is then derived as: $SoVI\ Risk_i = Hazard_i \times SoVI_i$

The resulting index is re-classified into five risk levels for cartographic representation. This approach is deliberately designed to be transparent, reproducible, and scalable, making it suitable for integration into regional resilience planning tools and sustainable urban governance frameworks. Given the different spatial resolutions of the input data, the final SoVI-based risk is expressed at the municipal level (Fig. 3b). The resulting risk map highlights a heterogeneous spatial pattern across the Greek regions, reflecting the combined effects of seismic hazard and underlying socio-economic conditions. Regions exposed to similar hazard levels (as e.g. municipalities of Central and Western Macedonia Regions) may experience markedly different risk outcomes depending on their underlying social vulnerability. Areas where high hazard coincides with elevated vulnerability (as e.g. the Ionian Islands) emerge as critical zones requiring targeted risk mitigation strategies. Conversely, regions with lower vulnerability may exhibit reduced risk despite comparable levels of seismic hazard.

These results have direct implications for resilience planning and sustainable development policy. Areas identified as high-SoVI risk zones, where elevated seismic hazard coincides with social vulnerability, require priority attention in national and regional resilience strategies. More broadly, the risk map provides a spatially explicit evidence base that can inform the allocation of resources within circular and sustainable urban governance frameworks, ensuring that resilience investments are directed where social and physical exposure is greatest.

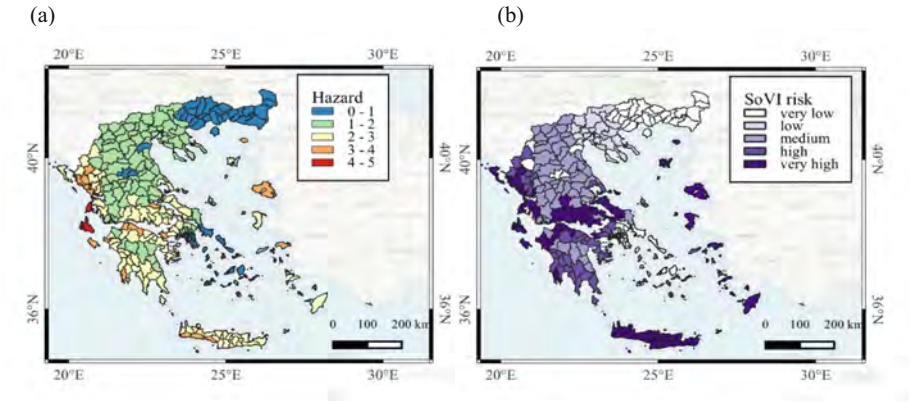


Fig. 3. (a) Seismic hazard map expressed in terms of (PGA) for a 475-year return period scaled into five hazard classes (1 to 5) and (b) SoVI risk map.

5 Conclusions

This study provides a comprehensive assessment of social vulnerability and seismic risk across Greece at the regional scale, highlighting the importance of integrating socio-economic factors with seismic hazard information. The analysis reveals significant regional variability in social vulnerability, emphasizing the need for spatially explicit approaches capable of capturing territorial disparities. In this context, the explicit inclusion of tourism represents a key contribution, particularly for Greece, where seasonal population fluctuations can substantially modify exposure patterns and amplify vulnerability in insular and coastal regions.

The integration of SoVI with seismic hazard through a risk matrix approach demonstrates how social vulnerability fundamentally shapes seismic risk outcomes beyond what physical exposure alone can capture. This integrated perspective is directly aligned with current resilience frameworks in the built environment, which increasingly call for the co-analysis of physical, social, and environmental dimensions of risk. The framework proposed here offers a robust and flexible tool to support risk-informed decision-making, while being compatible with sustainability and circularity principles: by making social vulnerability spatially explicit and methodologically transparent, it enables circular urban governance strategies to prioritize interventions in the most fragile communities, avoiding the perpetuation of structural inequalities in risk management.

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Resilience and Sustainability Issues in Preservation of Built Heritage under Climate Change

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Abstract. Built Heritage (BH) constitutes the secret treasure of Europeans in terms of human ethical and social values and economy. The field of preserving BH composes a significant part of construction sector and tourism development. Although vigilance about climate change impacts to the BH started from the last decade of 20th century and several EC projects have been run the last four decades the complexity of finding solutions remains. The particularities of BH structures such as local climate and natural environment, structural system and materials local culture in building, are some of the differentiation causes of the respond of BH to climate crisis. Furthermore, it is necessary (according to Treaties) in repair works to balance the authenticity of the BH with the resilience to climate hazards by using sustainable materials and maintaining structural integrity, functionality and long-term performance. In the paper a concise report will be given based on relevant literature, focusing on historic lithesome masonry structures around Mediterranean Sea geographic area where the greatest civilizations had been developed. Currently used adaptation methods to mitigate climate impacts to BH and sustainable repair materials for BH are given. In addition, the basics for the selection of evidence based non-invasive methods and tailor-made solutions for preservation of BH works are proposed.

Keywords: Climate change · Resilience · Sustainability · Preservation · Build Heritage

1 Introduction

Build Heritage (BH) consists of monuments, historical buildings in old-city centers, structures in archaeological sites such as odeons, theaters, thermes(public baths), mosaic pavements, traditional settlements which are located in different geographical latitudes and altitude all over the world and particularly around Mediterranean Sea areas.

BH structures have been constructed mainly with local materials architecture and techniques so as to be adaptable to local climate conditions. Analyzing mud mortals from a prehistoric structure (Dispilio near Kastoria, Greece) it has been revealed that different mud mortars were used for making floors and walls according to their functionality. Nowadays, this treasure of knowledge and dexterities is threatened to be lost

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with monumental structures under climate crisis. It took as two centuries (19^{th} and 20^{th}) to understand the "values" of global heritage, collective identity and develop restoration ethics as they declared in Europe UNESCO(ICOMOS)Treaties. In our days, BH is closely related to tourism and economy. Based on EUROSTAT (2023) report on the EU expenditure for cultural services amounted to 81.1 billion euros. According to ELSTAT survey on Ephorates of Antiquities the expense for restoration projects comes from GDP and EU funds and amounts 10–60 million euros per year (in 2023 the expenditure was 63.8 million euros).

Very early the consequences of Global Warming (of 1.5 °C) and climate change drew the attention of researchers and relevant organizations [1–3]., [4, 5].

At the same time Europe introduces Sustainability as one of the five pillars of the framework for Action on Cultural Heritage and promotes sustainability issues in restoration. A number of EC projects such as STORM (2016–2019), IPERION CH (2015–2019) started in parallel to others such as HERACLES PLUS about the Protection and Sustainable management of natural resources and ecosystems, have helped a lot to understand the impact of climate change and environmental problems.

In the meantime, new technology provided site specific sensors, damage assessment techniques (non-destructive and non-invasive methods for surveying and revealing threats and conditions), modern ways of situation awareness as well as digital modeling BH structures to predict damages under climate change extreme scenarios. However, the reliability of advanced tools in practice is still under question because of the particularities of different areas even around Mediterranean Sea. For example, in the archaeological site of Dion Greece, even during spring months a local hoar-frost covers all BH structures in the morning and provokes damages.

2 Build Heritage Structures

BH structures are spread all over the world and are closely related to the history and identity of the peoples and cultures developed on the Earth. The most known great civilizations are those of Ancient Greeks, Romans, Byzantines, Arabs and Ottomans. Furthermore, in medieval period Europe was enriched with BH of the cities. In our days many old buildings of pre-1960 constitute a stock of 35–42% of total buildings in Europe which need rehabilitation to be used again. Most BH consist of masonry elements by which the stability of the whole structure is achieved. Stone pieces or mud bricks or fired bricks are connected with lime-based mortars to form load bearing pillars walls and foundations.

It is well known [6, 7] that masonry as build complex presents an inherent lack of ductility as well as low compressive strength and weakness under tensile stresses. However, the technicians of the past had used as much as possible high-strength materials (stones, bricks, mortars) and wooden tie-beams to constrain the whole structure and managed to construct structures of noticeable longevity and resistance to earthquakes often happened in the Mediterranean area.

According to European code the compressive strength of masonry depends on the strength of lithosomes and jointing mortar (ECG $f_k = k \times f_b^{0.7} \times f_m^{0.3}$ where the f_k the characteristic masonry strength). Based of numerous research references [8–13], it is

indisputable that the main deterioration factor for masonry is the penetration of moisture and its retention within the masonry body. Usually, technicians cover the structure with wooden roof laid with tiles or slates and take care of a good system of rainwater runoff.

Experience showed that maintenance of masonry (based on monitoring) is the only way to keep it livable. Many Charters and declarations such as Venice Charter (1964) established the expediency of repairing BH structures:

"The aim of repairing is to preserve and reveal the aesthetics and historical values of BH and is based on respect for the ancient substance and authentic documents".

Up to now, BH has been identified as a driver for growth and jobs enabler, for social inclusion, asset for strengthening EU's interrelations. Therefor the principles of repairing BH have been formed and validated from practice (damages due to incompatible interventions) [14, 15].

3 Sustainability in Restoration of BH. Materials and Technique

In the context of European Green Deal (by 2050 carbon dioxide neutrality) sustainability is one of pillars of the framework for preservation Action on BH. Firstly, by regenerating BH such as old building stock in urban EU areas, the service life of buildings is prolonged and the construction of new buildings (with cement and steel) is avoided. This favors green fields and open landscapes.

In repairing BH, traditional bricks and lime-based mortars are commonly used for compatibility reasons. This type of bricks is fired at lower temperatures (600-800 °C). Local pozzolanic materials (volcanic pozzolan, metakaolin, hydraulic lime) and river sand or crushed limestone aggregates are used mostly for mortars. There is software by which LCA, LCCA, the produced CO2 (equivalent) during materials' production and transportation are estimated. Furthermore, an effort could be made to replace materials such as aggregates with recycled ones or natural pozzolans with artificial ones locally produced provided that their suitability should be checked by testing.

4 Climate Change Risks for BH

During the past 100 years the temperature of the Earth's surface has increased 0,8 °C and by the end of 21st cent. it is projected to be increased 1,8 °C to 4.0 °C.

The key damaging climatic factors which will be affected are: [16–20].

- Temperature of environment (fires)
- Moisture (rainfalls, hails, storms, floods, salt-transferring)
- Precipitation

  Thermoclasty (repeated expansion/contraction)
  Wind intensity (Typhons)

- Solar radiation and light fluctuations
- Sea level rise (Melting of glaciers, floods dangerous for BH near seaside)

Air pollution (combination of climate change + pollution)

The thermoclasty [combination of repeated changes of high temperature (drying) to high moisture (expansion) in short times leads to materials' deterioration such as bricks, mortars, wooden beams, and metallic components. Capillary raising of moisture inside results in salt migration or impregnation. The expansion or shrinkage of clayish soil due to high moisture of it could create problems in BH foundation or walls (sliding, settlement). Furthermore, rainfall and hail may cause bulging and collapse of rubble masonry.

- The moisture + temperature + precipitation may increase biodeterioration and discoloration on brick/stone walls roofing elements as well as efflorescence and sub efflorescence, straining and wood decay. Precipitation in combination with pollution may lead to dissolution of carbonates, bio-colonization, blackening of materials.
- The wind intensity can cause erosion (alveolation, honeycomb) denudation (under sand or dust driven wind) or even aggravate moisture accumulation, frost damage, crystallization process, biological growth. Furthermore, the increase in severe windstorms, cyclones, and catastrophic effects on BH structures have not yet been estimated.
- Solar radiation has direct impact because of local overheating and cracking. The UV and visible light is responsible for alteration of organic compounds, polymers and colors of materials.
- Radiation + Humidity promotes the growth of micro-organisms (causing chemical, mechanical and aesthetic problems).
- The IR (infrared) heat up materials leading to internal strains. Stones are also vulnerable to the impact of IR radiation. Furthermore, solar radiation increases air temperature entering through transparent surfaces.

5 Instructions for Preserving BH and Repair Interventions Under Climate Change Risk

The well known pathology of BH masonry could be summarized as follows

- Cracking (differential settlement thermal expansion)
- Deformation/displacement of walls (bulging, inclination)
- Loss of joint mortars
- Rising damp, rain infiltration
- Salt crystallization (efflorescence, sub-efflorescence, stone/brick deteriorate)
- Surface soiling (black crusts, gypsum, formation).

To enhance resilience and durability of BH structure to resist climate extremes measures to strengthen BH (rather maintenance work) should be taken trying to preserve the inherent "values". A balance is pursued of authenticity with resilience and sustainability.

The logical sequence of practical steps towards protection of BH for climate change risks are:

- Study the local climate of the area around BH including topography environmental conditions, protective possibilities.

- Study the history of BH structures as well as its respond to earthquakes, fires, floods and other extremes.
- Monitoring the behavior of the BH structures by using simple, easily applied gauges and record field observations to understand the onsite resistance of structure and materials under climate stresses.
- Repair properly any masonry defect (cracks, loss of joint mortars, lack of stone/brick pieces or units.
- Inspire and involve local people to inspect/watch the BH by taking photos, keeping dates and making a reference report to relevant authority.
- Think of traditional protective measures that have been adopted by masons in the past and estimate their effectiveness focusing on tailor-made solutions.
- Consider adaptive technologies and materials aligned with contemporary principles of protection from climate risks taken into account feasibility, cultural accessibility and make risk assessment.

Some examples from practice based on literature are given:

- In Nordic regions freeze-thaw cycles (severity and frequency) often threaten BH and materials. As measures of mitigation the phenomenon soft capping with soil layer or flexible protective covers are mentioned. For reduction of biodeterioration due to permafrost a series of mild measures could be applied such as improve subfloor ventilation etc.
- Use crystallization inhibitors for preserving BH from salts carried by moisture after testing their long-term performance.
- Reduce detachment of tiles and slates due to windstorm by using mortars to secure their placement.
- When rubble masonry suffers from bulging due to precipitation and infiltration, implement a soft capping or make proper grout injection to enhance connecting.
- For mitigating windstorm effects, windbreaks or diverting air flow media are used.

It seems that the measures taken are in general conservative in the frame of careful maintenance of BH structures.

6 Conclusions

BH structures have been survived for centuries and confronted the climate extremes based on awareness of indigenous communities and the use of tailor-made "traditional" practices. However, the repetition of climate phenomena has changed and according to COP30 (Brazil 2025) BH is considered "core part of climate policy and should be protected not just to the past but for the future. Today restoration means not only bring BH to original state but help them survive an uncertain future".

- Research on repair materials and techniques to confront climate destructive consequences have been started from 90^{s} and continued intensively in the recent decades of 21^{th} century.

A number of measures have been adopted in restoration field following recommendations of COP27-ICOMOS (November 2022) such as:

- Integrate climate risk assessment into conservation plans.
- Knowledge from protection of contemporary structures could be transferred in restoration of BH properly justified.
- Use of resilient materials e.g. breathable modern mortars.
- Manage humidity and temperature problems without energy use.
- Keep sustainability principles and low carbon restoration.
- Reuse (after rehabilitation) than demolish BH structures.
- Upgraded energy efficiency of BH.
- Use digital tools and climate modeling (employ GIS, digital twins, 3D scanning documentation) to predict BH behavior.
- Engage local population for safeguarding BH Up to nowadays there is not a protocol that should be followed in restoration, to make BH adaptable to climate crisis. There is a gap in policy and practice. We must make efforts to justify the relevant selected practice in intervention and focus on a step by step process trying to enhance resilience, durability and sustainability in repair works, keeping as much as possible the authenticity of BH structures in terms of architecture structural system and materials.

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Financing and Market Transformation: Circular Business Models, Green Financing, and Innovative Procurement Strategies

Innovative Financing Strategies for Circular Supply Chains

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Abstract. The transition from linear to circular economy (CE) models requires organizations to redesign supply chains in order to improve resource recovery, reuse, and waste minimization. However, the implementation of circular supply chains remains constrained by financial barriers, including capital-intensive reverse logistics systems, high upfront investments in recovery technologies, and delayed revenue generation associated with circular business models. This study investigates how innovative financing strategies can support the adoption of circular economy practices while strengthening operational performance and competitive advantage in renewable-energy supply chains.

A mixed-method approach was employed, combining Khan's five-step systematic literature review framework with Multi-Criteria Decision-Making (MCDM) techniques. The study integrates the Analytic Hierarchy Process (AHP) and TOPSIS methods to evaluate and prioritize financing strategies according to criteria such as financial feasibility, environmental impact, operational integration, scalability, innovation potential, and quality alignment. The framework was applied to EDP Renewables' "Close the Loop" initiative as a practical case study.

The findings indicate that circularity-linked KPIs and performance-based guarantees represent the most effective financing mechanisms, outperforming alternatives such as crowdfunding and green bonds. This effectiveness stems from their strong alignment with environmental performance and operational integration. Recovery technology investments also demonstrate significant innovation and sustainability potential. The study contributes to the literature by linking financial innovation with circular supply chain governance, while providing practical guidance for managers and policymakers seeking to accelerate CE adoption in the renewable energy sector.

Keywords: Circular Economy · Innovative Financing · Multi-Criteria Decision-Making · Circular Supply Chains · Renewable Energy

1 Introduction

In recent decades, environmental concerns such as climate change, resource depletion, and pollution have grown, amplified by the expected emergence of around three billion new middle-class consumers, prompting greater attention to sustainable business

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practices [8]. The transition to a circular economy represents a paradigm shift in supply chain management, promoting a restorative and regenerative production system that reduces resource waste and recognizes the interdependence between the economy and the environment [9]. This transition faces barriers (financial, organizational, technological, social, political, market, and logistical) highlighting the relevance of effective financial strategies in enabling sustainable practices [10, 17]. Leading firms increasingly adopt circular practices, raising questions about the opportunities and supply chain modifications required to gain competitive advantage.

This study examines financial strategies for material reuse and recovery in circular supply chains, linking circular economy principles with supply chain management to assess the continuous circulation of materials and minimize environmental impact.

2 Background

The transition to a circular economy requires significant financing to move from linear "take-make-dispose" models to regenerative systems that minimize waste, extend resource use, and create sustainable value [7]. Key strategies include green bonds, sustainability-linked loans, and other debt instruments, which have seen strong growth. Global green bonds surpassing $3 trillion in outstanding value by 2025, with increases in circular-focused issuance [13] (Table 1).

Table 1. Key benefits of circular finance across categories

Category	Key Benefits
Economic	Enables significant material cost savings (around €600 billion per year) through green bonds and sustainability-linked finance, while reducing waste and price risks [11].
For businesses	Offers cheaper, lower-risk funding via sustainability-linked bonds, loans, and circular equity, supporting product-as-a-service models linked to performance targets [12].
For consumers/buyers	Delivers greater long-term value and savings by funding durable, repairable products with longer lifespans through green bonds and reuse incentives [12].
Environmental	Cuts greenhouse gas emissions by up to 40% for key materials by 2050 through funding recycling, remanufacturing, and closed-loop systems with green bonds and blended finance [13].

Venture capital, private equity, blended finance, grants, and subsidies from governments support projects in high-impact sectors like plastics, fashion, food, and infrastructure, helping close multi-billion-dollar annual investment gaps [1, 18].

Financial institutions increasingly embed circular principles to reduce risks and meet net-zero targets via models like subscriptions and performance-based financing. Challenges remain, such as liquidity hurdles for models with delayed revenues, highlighting

the need for stage-tailored funding (from early grants to mature debt/equity) to capture multi-trillion-dollar opportunities [2].

3 Methodology

The MCDM Setup phase builds the foundation for AHP and TOPSIS by defining a hierarchical decision structure to prioritize financing strategies for circular economy adoption, such as in EDP's Close the Loop program. The top-level goal is to select mechanisms that overcome financial barriers while maximizing sustainable strategic benefits. Below it, key criteria are defined: financial feasibility (balancing upfront costs with long-term savings), environmental impact (favoring closed-loop recovery), operational integration (fit with EDP's Monitoring, Suppliers, Training, and Wind/Solar streams plus KPIs), scalability (across business units), innovation potential (role of new technologies), and quality alignment (standards and traceability) [3].

The alternatives include crowdfunding/green bonds, performance-based guarantees, circularity-linked KPIs, recovery technology investments (e.g., remanufacturing for renewables), and training programs for circular capacity [4]. Data collection relies on expert pairwise comparisons for AHP, supplemented by EDP's KPIs (e.g., % employees trained, % circular procurement, % circular renewable projects). If gaps arise, the process loops back to the systematic review for more sources. The phase outputs a decision matrix with alternative scores per criterion and placeholders for weights, enabling a smooth shift to AHP weighting and TOPSIS ranking of the strategies.

The AHP framework starts with a pairwise comparison matrix, where experts rate criteria on a 1–9 scale [5] (Fig. 1). Priority weights are calculated by normalizing and averaging the matrix columns. Consistency is checked using the Consistency Index (CI) and Consistency Ratio (CR) to ensure reliable judgments. This method provides a repeatable way to prioritize criteria in complex decisions [6].

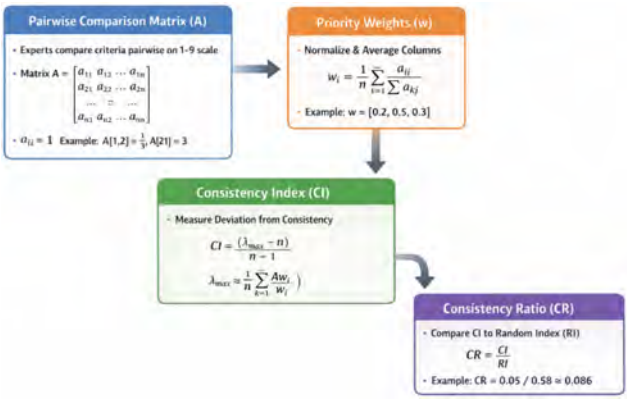


Fig. 1. AHP Method [5]

Figure 2 summarizes the TOPSIS method: first, raw scores are normalized; then weights are applied to emphasize important criteria. Next, distances to the ideal and negative-ideal solutions are calculated, from which the best and worst solutions are identified. Finally, the relative closeness to the ideal is computed to rank alternatives.

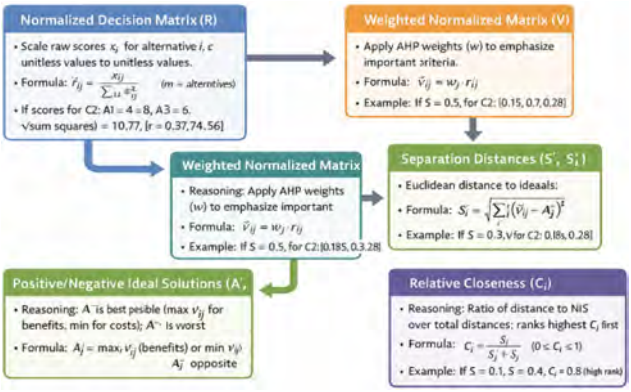


Fig. 2. TOPSIS Method [14]

4 Application

The methodology combines an Analytic Hierarchy Process (AHP) for weighting criteria, and TOPSIS for ranking alternatives. It is applied to EDP Renewables' Close the Loop program, a leading circular economy initiative in wind and solar asset lifecycle management. This initiative includes material recovery, equipment remanufacturing, waste minimization, and resource optimization, in partnership with over 20 recyclers to support net-zero by 2040. The approach prioritizes financing strategies to accelerate the adoption of circular practices. It emphasizes internal technical cycles, integration with EDP's key streams (Monitoring, Suppliers, Training, Wind and Solar), and relevant KPIs (number of initiatives, circular purchases, and projects incorporating circularity). The primary goal is to identify the strategies that most effectively drive circular economy adoption within the program (Table 2).

Using Saaty's 1–9 scale, expert pairwise comparisons were assumed to reflect circular economy priorities, environmental considerations outweigh financial in renewables, while operational integration and scalability are high for EDP's scale. Typical AHP patterns in CE and sustainable energy studies show environmental weights around 0.30–0.40 and economic weights around 0.20–0.35 [6].

After constructing the pairwise matrix (favoring environmental strongly over financial, e.g., 5:1, and operational over scalability, 3:1), normalizing columns, and averaging rows, approximate eigenvector weights were obtained with $\lambda_max \approx 6.42$, giving $CI = (6.42–6)/5 \approx 0.084$ and $CR \approx 0.068$, confirming consistency (<0.1). Resulting normalized criteria weights are: Environmental impact: 0.35, Financial feasibility: 0.22,

Table 2. Integrated strategies for renewable-energy circularity [15]

Category	Approach
Environmental impact	Tie funding to circularity KPIs for waste reduction and resource regeneration in wind/solar.
Financial feasibility	Use green bonds or CE financing to lower upfront costs and improve long-term ROI in renewable projects.
Operational integration	Build internal capacity through training and quality programs for smooth implementation across initiatives.
Scalability	Invest in recovery technologies (e.g., remanufacturing turbines) scalable across renewable projects.
Innovation potential	Support pilot initiatives of recovery technologies via crowdfunding or blended finance.
Quality alignment	Ensure traceability and efficiency through circularity-linked KPIs tied to EDP goals.

Operational integration: 0.18, Scalability: 0.12, Innovation potential: 0.08, and Quality alignment: 0.05.

In the TOPSIS application, performance scores were assigned on a 0–10 scale for benefit criteria, where higher values indicate better performance. Scores reflect case fit. For example, KPIs strongly aligned with EDP monitoring and training received higher ratings, while green bonds were scored based on suitability for large wind and solar investments. These scores were compiled into a decision matrix (raw scores) (Table 3).

The AHP analysis produced the following normalized criteria weights: environmental impact (0.35), financial feasibility (0.22), operational integration (0.18), scalability (0.12), innovation potential (0.08), and quality alignment (0.05). The consistency ratio (CR = 0.068) confirmed acceptable judgment consistency.

The TOPSIS evaluation ranked the financing strategies according to their relative closeness to the ideal solution. Circularity-linked KPIs and performance-based guarantees (A1) achieved the highest score (Ci = 0.912), followed by recovery technology investments (A3, Ci = 0.748), green bonds and CE financing (A2, Ci = 0.621), internal quality and training programs (A5, Ci = 0.582), and crowdfunding/blended finance (A4, Ci = 0.411)(Table 4).

The results indicate that KPI-linked and performance-based financing mechanisms provide the strongest combination of environmental performance, operational integration, scalability, and financial feasibility for circular supply chain implementation in the renewable energy sector.

Table 3. Weighted evaluation of circular finance strategies across six criteria

Alternative	Env (0.35)	Fin (0.22)	OpInt (0.18)	Scal (0.12)	Innov (0.08)	Qual (0.05)
A1: Circularity-linked KPIs/guarantees	9	8	9	9	7	9
A2: Green bonds/CE financing	8	7	7	8	6	6
A3: Recovery tech investments	9	6	8	7	9	8
A4: Crowdfunding/blended finance	6	9	6	6	5	5
A5: Internal quality/training	7	9	8	8	4	10

Table 4. Ranking of Circular Economy Financing Alternatives Based on TOPSIS Scores

Rank	Alternative	TOPSIS Score (Ci)	Main Strength
1	Circularity-linked KPIs/ guarantees	0.912	Operational integration and scalability
2	Recovery technology investments	0.748	Innovation and environmental impact
3	Green bonds / CE financing	0.621	Financial feasibility
4	Internal quality/training	0.582	Quality alignment
5	Crowdfunding/blended finance	0.411	Early-stage financing support

5 Discussion

The analysis shows that the top-ranked strategy is circularity-linked KPIs and performance-based guarantees, which excel in operational integration, scalability, environmental impact, and quality alignment. This aligns with EDP's focus on monitoring, evaluation, and quality management, highlighting the value of linking financing to measurable performance. Second-ranked are investments in recovery technologies, offering strong innovation and environmental benefits, particularly for wind and solar remanufacturing.

Therefore, KPI and performance-linked mechanisms, combined with quality principles, effectively reduce risks and accelerate circular economy adoption in renewables, enhancing operational efficiency and competitive positioning [16]. For EDP, priority should be given to KPI-linked financing within the Close the Loop framework and wind/solar streams. Future directions include blockchain for supplier traceability

and expanded green bonds tied to circular KPIs. This case demonstrates how AHP and TOPSIS provide transparent, prioritized recommendations for circular economy financing.

6 Conclusions

This study demonstrates that circularity-linked KPIs and performance-based guarantees are the most effective strategies for advancing circular economy adoption in renewable energy, excelling in operational integration, scalability, environmental impact, and quality alignment. Investments in recovery technologies also provide significant innovation and environmental benefits.

In conclusion, integrating KPI- and performance-linked mechanisms with quality principles helps lower barriers and strengthen both operational efficiency and competitive positioning. For EDP, emphasis should be placed on KPI-linked financing within the Close the Loop framework, as well as in wind and solar initiatives.

Future opportunities include integrating blockchain for traceability and expanding green bonds tied to circular KPIs. The case also shows that AHP and TOPSIS offer transparent, evidence-based guidance for prioritizing circular economy financing.

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Circular Value Creation Through Social, Environmental, and Economic Benefits, or the Business Case for Circularity

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Abstract. Circular value creation in building and construction extends product lifecycles and increases resource efficiency, generating business value through cost savings and new revenue. Circularity reduces waste, lowers greenhouse gas emissions, conserves resources, and helps protect habitats by limiting demand for virgin materials. Circular practices promote equity by empowering individuals and reducing disadvantage, while creating jobs in repair, remanufacturing, and resource management. From a business perspective, circular value creation enables companies to access new revenue streams and markets, leveraging services such as leasing, remanufacturing, and product-as-a-service offerings. By reducing reliance on virgin resources and securing supply chains, circular business models enhance resilience to market shocks and disruptions. As these strategies mature, they provide a distinct competitive advantage, unlocking greater economic value, compared to isolated, linear approaches. Circular value creation offers a compelling business case by seamlessly integrating social, environmental, and economic benefits. This research contribution aims at providing new knowledge on circular value creation, showcasing its impact while describing effective strategies for implementation. Researchers involved in the COST Action CA21103 CircularB developed a qualitative, inductive study as the most suitable method for investigating new topics and generating insights from detailed and complex information. Key results include the documentation of relevant value dimensions, the discussion of emerging models and assessment approaches, and the identification of main challenges and opportunities for promoting a business case for circularity. The relevance is high, as it addresses the construction sector's significant environmental impact and encourages pathways to greater sustainability and economic resilience.

Keywords: Circular Design · Circular Economy · Circular Building · Circular Business Models · Circular Value Creation

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1 Introduction

The circular economy (CE) aims to preserve the value and manage stocks of various assets, including natural, cultural, human, manufactured, and financial capital. Driven by need rather than profit, this system is considered the most sustainable post-industrial business model [1].

Transitioning to a circular model necessitates substantial adjustments across design, procurement, and construction processes. Challenges hindering the evidence-based implementation of circular practices include increased upfront costs, as material pre-treatment for reuse may sometimes be more expensive than landfilling, thus underscoring the importance of technological advances in recycling; limited market maturity, since the establishment of an active market for high-quality reused building components remains in progress; and intricate logistics, as coordinating reverse logistics for disassembly and reuse demands newly developed, specialized, and highly collaborative networks.

An important focus of the COST Action CA21103 CircularB research in the field is figuring out how to mainstream CE principles within the design, building, and construction industries and promote their widespread adoption building a "business case for circularity". Another key area this research has investigated is examining whether there exists a clear, consensus-based, and thorough definition of CE assessment specific to these business sectors—one that covers all major aspects of sustainability, as well as the associated environmental, economic, financial, social, and technological advantages. CircularB authors of this contribution ultimately sought to identify the essential characteristics of these relevant research areas, with the goal of offering recommendations that serve as evidence-based guidelines for building, developing, evaluating, and monitoring the Circular Economy (CE) in the built environment. This goal is intended to facilitate the effective implementation of CE principles in the design, building and construction.

A comprehensive review of current literature and other scientific evidence was purposely conducted to assess the state of research and identify key success factors for circular business development, thereby informing future directions for achieving sustainable and circular approaches in design, building, and construction, as well as promoting integrated social, economic, and environmental stewardship. This comprehensive search was conducted in leading academic journals to identify all relevant studies. Each article was classified along key dimensions, including specific circular business factors addressed. This classification enabled the identification of common themes, areas of divergence, and gaps in the current knowledge base. Finally, the business implications across the reviewed studies were synthesized, highlighting areas of consensus, disagreement, and emerging opportunities for further research. This synthesis is meant to provide clarity on the current state of the field but also to outline a roadmap for advancing the integration of circular economy into business development. Within this context, the paper explores how circular value creation is conceptualized and operationalized within the built environment. It examines the strategies enabling circular value creation, the environmental, economic, and social benefits associated with these approaches, and the methods currently used to assess their impacts across different scales of the built environment (see Fig. 1).

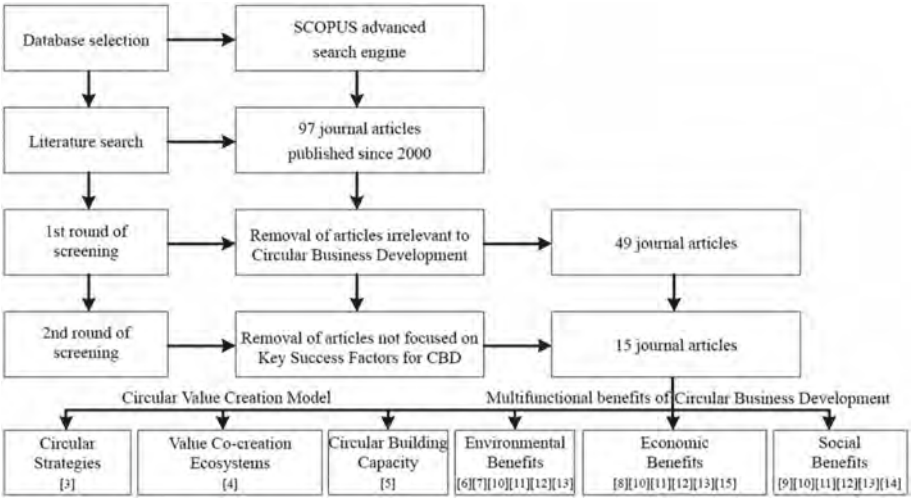


Fig. 1. Synthesis of the review process.

Through this synthesis, the paper contributes to clarifying how circular strategies generate multidimensional value and how this value can support the development of a stronger business case for circularity in the construction sector.

The paper is structured in four sections. In the Introduction, the goals, the methodology, and the expected results of the conducted research have been anticipated; section two describes key findings with respect to the foundations of circular value creation, showcasing its impact while describing effective strategies for implementation; section three deals with the characterisation of new models for assessing multiple values of the circular economy; and section four concludes highlighting the business case for circularity, formulating actionable recommendations.

2 Models and Strategies for Circular Value Creation in Design, Building, and Construction

Conceptual models of circular value creation in building and construction focus on closing resource loops through design for disassembly, material reuse, and remanufacturing, driven by collaborative, multi-stakeholder partnerships that enhance long-term economic, environmental, and social value. Those virtuous models prioritise "retaining value" at the core of the building (maintenance, renovation) over outer-layer actions – like demolition – which result in higher value loss, thus promoting the "Value-building Hierarchy" [2]. Buildings are conceived as "material banks" where components are selected and installed to allow for easy, cost-effective, and rapid dismantling, preventing end-of-life waste. Circular models prioritize using recycled, reclaimed, or refurbished materials, ensuring they remain in use for as long as possible. Partnerships allow for sharing knowledge, accessing circular materials, and setting new industry standards. Collaboration involves public (governments) and private sectors, with cities playing

a leading role in enabling, for example, urban mining and material re-use initiatives. Involving stakeholders early in the design phase is essential to ensure that materials can be effectively reused or re-manufactured at the end of their life cycle. Key components of this virtuous model encompass three main pillars, i.e., Circular Strategies, Value Co-creation Ecosystems, and Circular Capacity Building. Circular Strategies are based on three key actions, i.e., *Slowing, Closing, Narrowing,* defined by building for longevity (slowing), reusing materials/components (closing), and optimizing efficiency through design (narrowing).

The Circular Strategies of slowing, closing, and narrowing represent a framework to move from a linear "take-make-dispose" economy to a regenerative system that minimizes resource extraction and waste. These strategies are often applied in a hierarchy, prioritizing the extension of product life (slow) and efficiency (narrow) before recycling (close) [3].

Value Co-creation Ecosystems mark a significant departure from conventional firm-centric models of value creation, adopting a collaborative, network-oriented framework in which a wide array of stakeholders—including suppliers, partners, clients, and competitors—jointly generate, deliver, and capture value within an integrated system. Instead of relying solely on traditional, static dyadic relationships between buyers and suppliers, these ecosystems utilize technology and collective resource integration to expand the shared value across all participants [4].

Building skills in material passports, modular construction, and circular procurement is essential for moving toward a resource-efficient, regenerative construction industry with reduced environmental impact and better management of limited resources [5].

Value drivers for a conceptual model of circular value creation include revenue generation through product-service systems such as the leasing of building materials, decreased waste management costs, and improved brand reputation. These capabilities support the construction sector in minimizing waste, reducing carbon emissions, and extending the lifecycle of resources. Adoption of these practices facilitates the transition from linear "take-make-waste" models to regenerative systems, thereby maximizing resource efficiency throughout the entire building lifecycle.

3 Assessing Social, Environmental, and Economic Benefits of a Circular Built Environment

Research indicates that adopting CE principles in the built environment can offer considerable benefits. These include diminished environmental impact, new economic prospects, and fairness by empowering communities and mitigating inequalities.

3.1 Exploring the Multifunctionality of the Circular Built Environment

Environmental Benefits include decarbonization, since circular approaches can cut up to 39% of global CO_2 emissions from materials by 2050 [6]. Waste reduction is achieved by designing buildings so they can be taken apart and reused, which dramatically lowers construction and demolition waste—a sector that currently produces 30% of the world's total waste [7]. Resource efficiency improves when components and materials such as

steel and concrete are repurposed, reducing demand for new raw materials and helping protect natural habitats and biodiversity. By retrofitting and renovating existing buildings to make them last longer, we minimize the need for new construction that consumes substantial resources.

Economic Benefits of a circular built environment comprise cost savings and increased efficiency. The reuse of materials and resource optimization can reduce procurement and disposal costs. Structures designed for material recovery maintain greater asset value, a process supported using "material passports." It has been recently estimated that transitioning to a circular model has the potential to generate up to 8 million new jobs globally in labour-intensive fields such as repair, recycling, and remanufacturing [8]. Additionally, sourcing materials locally decreases reliance on unpredictable global markets and strengthens supply chain resilience.

Social Benefits encompass a range of advantages, including enhanced health and comfort resulting from the use of circular, bio-based materials and superior design practices, which contribute to healthier and more comfortable indoor environments. The reduction of on-site waste, noise, and disruption during construction activities improves the quality of life for neighbouring communities. Collaborative and community-driven initiatives—such as urban gardens and reuse hubs—foster greater social cohesion. Furthermore, the transition to circular value creation within the building and construction sectors can offer safer and more secure employment opportunities for workers in both waste management and construction [9].

3.2 Assessment Methods and Challenges

There is currently no ISO standard for assessing circularity in buildings or the built environment. Instead, a range of academic, industry, and policy-based methods address circularity at different scales, from materials to cities. Developmental initiatives in CE monitoring mainly use data-driven methods—collecting and converting data into indicators that guide stakeholders' actions. These approaches aim to help optimize design and construction by reducing materials, encouraging reuse and recycling, and using real-time data. They also support urban mining, better waste management, resource efficiency, sustainability efforts, and policy development with reliable standardized data for effective regulations.

Data-driven tools are reshaping construction. BIM centralizes project data for process simulation, waste reduction, and assessing material circularity. Digital Twins provide virtual models to optimize asset performance, aiding renovation and reuse. Material and Digital Product Passports track building component details for better reuse and recycling. IoT sensors and RFID gather real-time data to streamline waste management and recycling. Blockchain secures traceability and smart contracts, increasing accountability. The collected data can be converted into actionable indicators, such as circularity indicators, which measure performance, set targets, and evaluate the effectiveness of CE strategies. At the material and product level, the Ellen MacArthur Foundation introduced the Material Circularity Indicator (MCI) [10] to assess product circularity based on factors such as virgin material input, non-recoverable waste output, use intensity and service life. The indicator has since been widely adopted for assessing material-level circularity within the built environment.

At the building level, more diverse circularity assessment methods have been developed. Indicators can be categorised as quantitative, semi-quantitative and qualitative, and are applied either individually or as part of indicator sets within assessment frameworks. The European regulatory framework Level(s) [11] provides a set of quantitative indicators for circularity assessment, such as the bills of materials and quantities of construction and demolition waste. Semi-quantitative assessments are commonly applied within the Green Building Rating Systems [12].

At the neighbourhood level, circularity assessment is conducted using sets of indicators within quantitative, semi-quantitative, and qualitative frameworks. For instance, the German Sustainable Building Council (DGNB) [13] incorporated five CE bonus indicators (i.e., water cycle systems, resilience and adaptability, social and commercial infrastructure, resource management, and construction site) within its DGBN Urban District certification.

At the city and beyond scale, quantitative assessments are more prevalent, either based on a single indicator or sets of indicators.

Existing circularity assessment indicators and frameworks collectively address environmental, economic, social, technical, and managerial dimensions. Among these, the environmental dimension is the most extensively explored, aligning with the strong emphasis on emission reduction, material efficiency, and energy performance in current research and policy agendas. The technical dimension is represented through indicators related to design-for-disassembly, design-for-adaptability, design-for-longevity, and innovative construction methods. In contrast, the economic, social, and managerial dimensions remain underexplored, despite their important role in ensuring the feasibility and success of circular transitions.

To fully understand the benefits and compromises of a circular built environment, it is necessary to use thorough, multi-criteria approaches that evaluate environmental, economic, and social factors together. Methods like Material Flow Analysis (MFA), Life Cycle Assessment (LCA), and Social Life Cycle Assessment (S-LCA) are commonly applied. These analytical tools help assess how waste management, energy systems, and sustainable production perform; pinpoint bottlenecks, inefficiencies, and ecological problem areas in construction practices; and assist businesses and governments in finding the right balance between economic growth and environmental responsibility.

Notwithstanding the potential described above, the effective uptake of circularity indicators and analytical tools remains limited in practice. Key challenges include a lack of standardised methods for measuring social impact, difficulty in accessing data, and higher initial costs, which need to be addressed through regulatory support [14].

4 Building a Business Perspective

Although the implementation of circular economy (CE) principles within the construction sector is frequently impeded by insufficient, fragmented evidence and the absence of standardized metrics, circularity broadly presents substantial economic advantages, with the potential to yield an annual net profit gain of $31–46 billion by 2030, and $234–360 billion by 2050 [15], reducing companies and businesses' reliance on volatile raw material markets, and building more resilient supply chains.

Circularity can help reducing waste, cutting down greenhouse gas emissions, conserving resources, and protecting habitats by reducing the need for new materials. Circular methods can also promote fairness by empowering people and reducing disadvantages, while generating jobs in areas like repair, remanufacturing, and managing resources.

For businesses, circular value can allow access to extra revenue streams and markets through services such as leasing, remanufacturing, and product-as-a-service models. By using fewer new resources and securing supply chains, circular business approaches can strengthen resilience against market shocks and disruptions. As these strategies advance, circularity can offer clear competitive benefits, providing greater economic value compared to traditional, linear methods. At the same time, the transition toward circular construction practices still faces several challenges, including fragmented assessment frameworks, limited data availability, and the need for stronger collaboration across supply chains. Addressing these barriers will be essential for enabling a business-oriented adoption of circular value creation strategies in the construction sector.

Circular value creation can provide a strong business case, blending social, environmental, and economic advantages. Circular value creation can evolve from a niche sustainability effort into a core, strategic business imperative appropriate to tackle the challenges of the Anthropocene, i.e., a practice driven by the need for risk reduction, cost efficiency, and regulatory compliance. The transformation is already underway, and it is essential for the construction industry ecosystem to strategically position itself now to capitalise on the opportunities anticipated in the future.

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Circular Business Logic for Sustainable Buildings: Developing a Framework Through Expert Consensus

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Abstract. The transition towards circular and sustainable business models in the construction sector has become a central priority for European policy and industry practice. Buildings generate significant environmental impacts throughout their life cycle, and shifting from linear approaches to regenerative models is essential for improving resource efficiency, reducing waste, and extending the useful life of existing structures. This study examines how circular business logic can be meaningfully integrated into the construction and reconstruction of buildings, emphasising the strategic, organisational, and financial conditions that enable the adoption of circular principles. The analysis highlights the interdependence between design for adaptability, digital traceability of materials, collaborative value chains, and innovative revenue mechanisms capable of supporting long-term sustainability. It also underscores the importance of regulatory stability and organisational learning for the practical implementation of circularity in buildings. The study contributes to the academic debate by proposing an integrated conceptual framework and by identifying priorities for policy, management, and future research.

Keywords: Circular Business Logic. Sustainable Buildings. Developing. Sustainable. Circular Economy

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1 Introduction

The transition towards circular business models in the construction sector has gained increasing prominence in European policy agendas, corporate strategies, and academic debate, largely due to the high levels of resource consumption, waste generation, and emissions associated with the life cycle of buildings. Replacing the linear model based on extracting, producing, using, and discarding with circular approaches has become essential to improving resource efficiency, extending the lifespan of structures, and reducing the environmental impacts of the built environment.

Despite theoretical and regulatory advances, gaps remain in the literature regarding the strategic, organisational, and financial conditions required to effectively integrate circular principles into building construction and renovation. The absence of an integrated framework that connects key dimensions such as design for adaptability, digital traceability of materials, collaboration across value chains, and new value-creation mechanisms aligned with long-term sustainability highlights the need to consolidate existing knowledge and guide organisational practices and public policies more consistently.

In this context, the present study aims to develop an integrated framework for circular business logic in sustainable buildings, grounded in expert consensus from the fields of circular economy, sustainable construction, architecture, and urban management. To achieve this, the Delphi method was employed, as it is well suited to complex and multidimensional topics, enabling a structured and iterative process of consultation and convergence of expert opinions. By integrating diverse specialised perspectives, the study contributes to scientific advancement and to the formulation of strategic guidelines that support the transition towards more circular practices in the construction sector.

2 Theoretical Framework

2.1 Circular Economy and Responsible Production

The transition from a linear economic model based on extracting, producing, consuming, and discarding towards more sustainable and regenerative approaches has become essential in light of increasing pressure on natural resources and the growing environmental impacts associated with production and consumption systems. Contemporary literature highlights the circular economy as a strategic alternative capable of optimising resource use, reducing waste, and extending the life cycle of materials and products [1–3].

Aligned with the principles of sustainable development established by the WCED [4], the circular economy integrates environmental, social, and economic dimensions by promoting responsible innovation, ecosystem protection, and social inclusion. This includes the incorporation of vulnerable workers such as waste pickers into more sustainable value chains, contributing to social justice and the creation of green jobs [5, 6].

Central to circularity are the 6Rs, reduce, reuse, recycle, redesign, remanufacture, and recover, widely recognised as guiding strategies for material valorisation and the extension of product life cycles [3, 7–9]. These principles reinforce the need to redesign production and consumption systems to minimise environmental impacts and promote regenerative flows.

Within this context, Sustainable Development Goal 12 (Responsible Consumption and Production) provides an international framework that encourages the adoption of circular practices, waste reduction, and greater resource efficiency. Authors emphasise that the circular economy strengthens the integration between productivity and sustainability, while the 6Rs support the transition towards more responsible and resilient systems [2, 3, 9]. Recent studies further demonstrate that incorporating circular principles enhances the environmental, social, and economic resilience of cities and organisations, supporting global sustainability targets [8].

Together, these perspectives establish the conceptual foundations for understanding how circularity can be operationalised in sectors with high environmental impact, such as construction, where the shift from linear to circular models is both urgent and strategically necessary.

2.2 Circular and Sustainable Business Approaches in the Construction Sector

The construction sector has long operated under a predominantly linear logic of "extract, produce, and discard" [10], resulting in high levels of resource consumption, significant waste generation, and substantial environmental pressures, including pollution and the depletion of landfill capacity [11]. In recent years, however, the sector has been increasingly challenged to adopt more sustainable and circular approaches, driven by global climate commitments, regulatory evolution, and the need to improve material efficiency [12, 13].

Circular business models in construction emphasise strategies such as design for adaptability, material recovery, reuse, and the extension of building life cycles. These strategies align with broader circular economy principles and with international sustainability agendas, which promote regenerative practices and the reduction of environmental impacts across value chains. Within this context, the management of construction and demolition waste (C&DW) plays a central role, as it represents one of the largest waste streams worldwide and contains materials with high potential for reintegration into productive cycles [14].

Studies show that 70% to 80% of C&DW is composed of inert materials such as concrete, mortar, ceramics, and bricks, which present strong technical viability for reuse and recycling [15, 16]. Although construction waste tends to be more homogeneous and easier to process, demolition waste is more heterogeneous, which affects classification, sorting, and recycling efficiency [17]. The production of recycled aggregates remains the most widespread technology for reprocessing these materials, with applications in paving, road bases, and non-structural components. Despite this potential, recycling rates vary significantly across regions: for example, Brazil reintegrates only about 15% of C&DW into the production cycle [18], while several European countries achieve substantially higher levels of recovery, particularly where selective demolition and circular procurement practices are well established [17].

2.3 European Practices in Construction Waste Management

The construction sector holds a significant position within the European economy and remains one of the largest consumers of natural resources, which explains the growing

policy emphasis on waste management and material efficiency. Recent studies indicate that initiatives aligned with circular economy principles have strengthened efforts in prevention, reuse, and recycling, reinforcing the relevance of the waste hierarchy established by the European Union [19]. Although performance varies across countries, the literature highlights that practices such as selective demolition and the recovery of reusable materials help reduce dependence on landfilling and support more sustainable value chains [20].

3 Methodology: Application of the Delphi Method

This study employed the Delphi method to obtain expert consensus on the strategic dimensions of circular business logic in the construction sector. A panel of five specialists was selected based on recognised academic and professional experience in circular economy, sustainable construction, architecture, and urban management. The process ensured anonymity and independence of judgement, allowing experts to contribute without group influence. Two iterative rounds of questionnaires were administered online, enabling the refinement of perceptions and the identification of convergent and divergent views.

In the first round, experts responded to open-ended questions addressing barriers to circularity, strategic enablers, design principles, regulatory challenges, and indicators for assessing circular maturity in buildings. Their qualitative responses were analysed through thematic coding to identify emerging categories. This iterative process strengthened the reliability of the collective judgement and supported the development of the conceptual framework.

The final analysis integrated the coded qualitative data with descriptive insights provided by the experts, allowing the identification of key strategic factors, good practices, and implementation challenges. This combination of expert contributions and literature foundations provided a robust basis for the proposed framework on circular business models in the construction sector.

4 Results: Delphi Analysis and Integration of Circular Business Logic

The results were organised into three interconnected analytical dimensions that emerged from expert contributions: (i) integration of circular business logic into building design and management, (ii) collaboration and value-chain dynamics, and (iii) regulatory, organisational, and economic conditions that shape the feasibility of circular practices. These dimensions are presented continuously, allowing for a more fluid and coherent reading of the results, followed by a visual synthesis that summarizes the main findings.

The experts converged on the view that advancing circularity in the construction sector requires replacing linear practices with life-cycle-based approaches, supported by design strategies such as modularity, disassembly, durability, and functional flexibility. Buildings were described as dynamic systems whose components must be designed for replacement, reuse, and extended lifespan. Persistent gaps, such as limited metrics, fragmented value chains, and the absence of secondary markets, were identified as structural

obstacles that hinder the transition. Collaboration across the value chain was considered insufficient, marked by low interaction, project-based fragmentation, and limited data sharing. To overcome these challenges, experts highlighted the importance of digital platforms for material traceability, early-stage integrated planning, performance-based contracting, and public–private partnerships capable of aligning incentives for circular material flows.

Regulation emerged as a critical barrier, particularly due to the lack of clear standards for reuse, complex certification procedures, and difficulties in approving reused structural materials. Experts also emphasised the need for new organisational competencies, including systems thinking, LCA/LCC, design for disassembly, and digital skills. Higher education institutions were seen as key actors in strengthening capacity through applied research, curricular integration, and living labs. Economic barriers were also highlighted, especially high initial costs, which refer to the additional expenses associated with selective demolition, material sorting, digital traceability systems, specialised labour, and the acquisition of modular or demountable components, costs that are often higher at the outset but tend to decrease as circular practices scale. Despite these challenges, experts identified replicable good practices such as selective demolition, material passports, reuse-oriented rehabilitation, and green public procurement. Strategic priorities included rehabilitating existing building stock, developing secondary markets, digitalising the value chain, and strengthening regulatory and financial frameworks. Proposed indicators for assessing circular maturity included the percentage of reused materials, adaptability, durability, maintenance intensity, and embodied carbon (Table 1).

Table 1. Summary of Expert Insights on Circular Business Logic in Construction

Dimension	Key Findings
Circular design principles	Modularity, disassembly, durability, flexibility; buildings as dynamic systems.
Value-chain collaboration	Fragmentation, limited interaction; need for digital platforms, integrated planning, performance-based contracting.
Regulation and standards	Lack of clear reuse standards; complex certification; approval barriers for reused materials.
Organisational capacities	Need for LCA/LCC, systems thinking, digital skills, design for disassembly; role of universities.
Economic conditions	High initial costs (selective demolition, sorting, digital systems, modular components); need for incentives.
Good practices	Selective demolition, material passports, reuse-oriented rehabilitation, green procurement.
Circular maturity indicators	% reused materials, adaptability, durability, maintenance intensity, embodied carbon.

Source: Own elaboration based on Delphi Analysis results.

The table synthesizes the main contributions of the experts, organized into dimensions that reflect the challenges and opportunities of circular logic in construction. The results highlight regulatory, economic, and organizational barriers as well as promising practices and maturity indicators, providing an integrated perspective on how to advance the transition toward circular models

5 Conclusion

This study examined how circular business logic can be integrated into the construction sector, a field traditionally marked by linear practices and high environmental impact. By consulting a panel of experts through a two-round Delphi process, it was possible to identify strategic dimensions that support the transition towards more sustainable and regenerative building practices.

The results revealed broad consensus on the centrality of life-cycle thinking, design for adaptability, digital traceability of materials, and collaborative value-chain mechanisms. Experts also emphasised the relevance of economic models based on services, maintenance, and reuse. At the same time, some divergences emerged, particularly regarding the maturity of existing value chains, the economic feasibility of circular solutions in different contexts, and the institutional capacity to implement reuse standards and certification procedures. These differences highlight the complexity of operationalising circularity and reinforce the need for context-sensitive and progressive implementation strategies.

The Delphi method proved appropriate for refining expert insights and structuring them into a coherent conceptual framework. Rather than validating a predefined model, the method enabled the identification, clarification, and prioritisation of strategic factors, barriers, and good practices that collectively inform the proposed framework for circular business models in construction.

Future research could deepen the empirical analysis of circular practices implementation across different regional contexts and building typologies, exploring performance indicators throughout the life cycle and governance mechanisms capable of aligning actors across the value chain. Moreover, international comparative studies and investigations into innovative business models, such as digital traceability platforms and secondary material markets, may provide additional evidence to consolidate transition strategies toward circularity in the construction sector.

The study offers practical implications for organisations and policymakers, including guidance for integrating circularity into design processes, asset management, and decision-making routines, as well as recommendations for strengthening secondary markets, financial incentives, and regulatory clarity. Academically, the findings underscore the importance of approaches that articulate technical, economic, and organisational dimensions in the pursuit of circularity.

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Developing a Circular Business Model Canvas for the HVAC Industry: A Multiple-Case Study

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Abstract. As global demand for low-carbon technologies increases, the Heating, Ventilation, and Air Conditioning (HVAC) industry faces growing pressure to reduce its environmental impact while meeting rising resource needs. While innovations such as heat pumps, renewable energy integration, and energy-efficient materials have advanced, their development often depends heavily on virgin resources, posing a significant sustainability challenge. This paper's main contribution is the development of a Circular Business Model (CBM) for the HVAC industry, derived from an in-depth analysis of four leading companies through multiple case studies. Using a qualitative approach encompassing document analysis, business model archetype mapping, and the Sustainable Business Model Canvas (SBMC), the research illustrates how HVAC manufacturers can transition from traditional linear business models to circular approaches that reduce resource consumption and carbon emissions. The resulting CBM highlights key strategies for creating circular value, including product modularity, remanufacturing, take-back schemes, digital capabilities, and service-based offerings. By synthesising these insights into a practical business model canvas, the study provides both a comprehensive framework for companies seeking to apply circular economy principles and a valuable contribution to the growing research on CBM innovation, particularly for low-carbon HVAC solutions.

Keywords: Circular Business Model (CBM) · Heating Ventilation and Air Conditioning (HVAC) · Multiple-Case Study · Sustainable Business Model Canvas (SBMC)

1 Introduction

The Heating, Ventilation, and Air Conditioning (HVAC) industry worldwide contributes significantly to greenhouse gas (GHG) emissions and energy consumption, accounting for about 5.5 gigatonnes of CO_2 emissions annually [1–3]. For context, this is greater than annual emissions from all of Europe combined [4]. To address this damning impact,

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the HVAC industry has seen a surge in research and development focused on low-carbon solutions. Innovations such as heat pumps, renewable energy integration, and energy-efficient materials have advanced significantly within the 21st century [5]. Government policies and funding have also prioritised these low-carbon technologies as an essential pathway for achieving net-zero GHG emissions by 2050 [6]. However, one of the key disadvantages of these technologies is the need for a greater amount of raw materials and virgin resources.

HVAC systems are usually complex, sophisticated, cost-intensive, and encompass numerous materials. Additionally, their shorter product lifespan when compared to other building components implies multiple replacements over the lifetime of a building [7]. These systems, including emerging low-carbon solutions, are primarily made of metal, rubber, copper, refrigerant, aluminium, insulation, plastics, critical raw materials for example in rare earth magnets, and 3TG conflict minerals [7–9]. With escalating geopolitical instability disrupting the supply chain, HVAC manufacturers must transition from traditional linear business models toward circular models [10].

Across the European Union (EU), emerging policies such as the new Construction Products Regulation (CPR), Energy Performance of Buildings Directive (EPBD) recast, and the Extended Producer Responsibility (EPR) are also mandating a change in manufacturing approaches [11, 12]. Therefore, the rising demand for sustainable and low-carbon HVAC technologies, driven by environmental impact, policies and population growth, highlights the need to decouple innovation from resource use.

A Circular Business Model (CBM) is designed to systematically identify opportunities for developing circular value propositions, leverage these opportunities for circular value creation, and optimise the potential for value capture [13]. In contrast to the linear take-make-waste model, CBM generates economic value through the sustained circulation and continuous reuse of materials and products over time [7, 14]. Five major archetypes of CBM formulated by Accenture [15] include circular supplies, sharing platforms, product-as-a-service (PaaS), product life extension, and resource recovery. Circular supplies entail using renewable, recyclable, or biodegradable inputs to replace single-lifecycle inputs. Sharing platforms enable the shared use of underutilised assets. PaaS involves selling access or performance instead of a product (ownership is replaced with using a service). Product life extension entails repairing, upgrading, refurbishing, or remanufacturing products. And resource recovery focuses on recovering materials, energy, or components from waste streams [15, 16].

Ultimately, deploying CBMs within the HVAC industry is pivotal to addressing the environmental impact, strengthening against supply chain shocks, aligning with emerging regulations, and ensuring resource efficiency. Therefore, this study aims to examine multiple case studies and deploy a Sustainable Business Model Canvas (SBMC) to develop a circular business model for HVAC manufacturers.

2 Methodology

Using a multiple-case study analysis investigating the circular practices of various HVAC companies, the research adopts a qualitative approach, deploying document analysis, business model archetype mapping, and the SBMC. Four organisations, namely Grundfos, Worcester Bosch, Daikin, and Kaer, constitute the case studies for analysing their

circular practices and translating them into the CBM canvas. These organisations were selected as they are leading manufacturers and key service providers in the HVAC sector, representing a mix of global and regional perspectives and demonstrating diverse approaches to circular practices. Industry-facing documents comprising of corporate annual sustainability reports, project showcases, product catalogues, news articles, and press releases were analysed to extract vital insights and information for the study. The circular practices of each organisation are then mapped to the five major CBM archetypes.

As an iteration of the Business Model Canvas developed by Osterwalder and Pigneur [17], SBMC is a strategic framework designed to outline, evaluate, and develop business models by incorporating the triple bottom line of environmental, economic, and social aspects [18]. SBMC has been adopted across various industries and research initiatives, such as for renewable energy communities [19], electric motorcycle conversion [18], and distributed solar photovoltaic (PV) projects [20]. This research adopts the SMBC iteration designed by Gerlach [21] covering 11 building blocks, which are sustainable partners, value creation, technology and resources, value proposition, customer relation, channels, responsible customers, end of life, cost structure, additional costs, subsidisation, and revenue and sustainability premium.

3 Case Studies

The circular practices and portfolio of products and services offered by the indicated four case study organisations are outlined below, mapped with various CBM archetypes, and extrapolated to develop the CBM using the SBMC.

3.1 Grundfos

Grundfos, headquartered in Denmark with over 19,000 employees globally, is the world's largest manufacturer of HVAC pumps, producing more than 16 million pump units annually, including circulator, submersible, and centrifugal pumps [22]. Over the years, Grundfos has focused on eliminating landfill waste, streamlining its production process, and reducing energy usage and material consumption [23]. Since 2014, they have implemented a take-back programme on pump circulators to remanufacture and recycle components and reduce waste across seven EU countries [24]. In 2024, Grundfos reduced total landfill waste by 73% compared to a 2018 baseline and collected 89,054 kg of pumps from customers [24]. These initiatives primarily align with the CBM archetypes of product life extension and resource recovery. Through its pump take-back programme, Grundfos remanufactures and reuses components, while recycling recovered materials and reducing landfill waste supports resource recovery.

3.2 Worcester Bosch

Worcester Bosch is a leading UK-based manufacturer renowned for its high-efficiency gas and oil boilers, with a growing portfolio of renewable heating technologies, including heat pumps and hydrogen-ready boilers [25]. As part of efforts to advance circularity,

the company became the first OEM customer in the UK to partner with Grundfos on the take-back scheme [26]. This trial initiative enabled the recovery of rare-earth elements, like alloys in magnets, typically unrecoverable through conventional recycling methods. Other circular business initiatives have also been tested within the larger Bosch group, such as the Papillon appliance leasing project [27]. These initiatives can be mapped to various CBM archetypes, including PaaS, product life extension and resource recovery.

3.3 Daikin

Daikin is a Japanese multinational conglomerate widely regarded as the world's largest manufacturer of HVAC equipment, such as heat pumps, air conditioning, air filtration technology, compressors and refrigerants, with over 100,000 employees worldwide [28]. The company has developed several initiatives aimed at closing material loops, reducing virgin resource use, and extending product life cycles, particularly in refrigerants and HVAC equipment. Linked to the circular supplies CBM archetype, the company adopts natural and low-GWP refrigerants, like R-32, to reduce environmental impact [29]. Launched in 2019, L∞P by Daikin pioneered circularity by recovering, reclaiming, and reusing refrigerants, saving over 400,000 kg of virgin refrigerant from being produced yearly across Europe [30]. Daikin also applies the PaaS archetype, offering subscription-based air conditioning in Tanzania and Air-as-a-Service in Japan, enabling effective maintenance, repair, and eventual recovery [29].

3.4 Kaer

Kaer is a Singapore-based company that transitioned from providing air-conditioning systems to offering a Cooling-as-a-Service (CaaS) servitisation model for commercial and industrial customers [31]. With a management portfolio of over 2 m sq. metres and saving over 35,000 mt of CO_2 annually, the PaaS archetype that Kaer deploys decouples value from ownership, encourages longer asset utilisation, and enables Kaer to optimise performance, maintenance, repair, and eventual recovery of system components [32]. Expanding across Asia and India, Kear reduces the need for new equipment manufacturing and is enabling building owners to concentrate on use outcomes instead of owning HVAC products [33].

4 HVAC Circular Business Model Canvas

The CBM in Table 1 provides solutions for companies to service homeowners, commercial clients, social housing providers, and public institutions seeking low-carbon cost-effective HVAC systems. The company creates value through modular, upgradable product design, digital energy-management technologies, and long-term service agreements, enabling maintenance, upgrades, and predictive monitoring throughout the system's lifecycle. Revenue is generated not only through traditional product sales but also through leasing and PaaS models, maintenance contracts, smart-system subscriptions, and government incentives. Circularity is achieved by take-back schemes, refurbishment, remanufacturing, and reuse of components, supported by reverse logistics partnerships and integration of recovered materials into new production.

Table 1. HVAC Circular Business Model using the SBMC

Sustainable Partners	**Sustainable Value Creation**	**Sustainable Value Proposition**	**Sustainable Customer Relationship**	**Responsible Customers**
Suppliers: sourcing sustainable and recyclable materials, resources, and components. Retailers & Installers: end-user communications. Technology partners: integrating advanced digital solutions for product usage tracking. Academic and research institutions: collaborating on materials and innovation research. Government: influencing sustainability policies and regulation. Recycling and waste management firms: Ensuring responsible end-of-life product handling.	**Sustainable Value Creation** Product innovation: Design for modularity, efficiency, and reusability. Closed-loop supply chain: integrate reverse logistics. Service provision: offer maintenance, upgrades, & customer support. Digital: create platforms for energy management and system monitoring. Stakeholder engagement: educating and involving actors across the entire value chain. **Sustainable Technology & Resources** Energy-efficient manufacturing facilities. Research and development teams for material innovations. Skilled workers for production, installation, and service. Technical support for smart technologies and customer interfaces.	**Sustainable Value Proposition** Energy-efficient solutions: offering HVAC products that reduce energy consumption and GHG emissions. Circular product design: developing modular and upgradable systems to extend product lifecycles. Recovering resources: using Take-Back schemes. Circular business model: offering leasing & PaaS models ensuring regular maintenance and updates, particularly for large-scale clients. Digital integration: using IoT and innovative technologies for optimised energy use and predictive maintenance.	**Sustainable Customer Relationship** Offering long-term service agreements to maintain and upgrade services throughout the product lifecycle. Customer education to provide information on energy savings and sustainable practices. Feedback mechanisms to gather user inputs for improving products and services. **Sustainable Channels** Direct sales and online platforms to facilitate customer access to products and services. Upskill retail partners and installers to ensure professional installation and local support. Partner with housing associations on sustainable housing projects. Participate in Government programmes and initiatives promoting energy efficiency.	**Responsible Customers** Residential homeowners seeking energy-efficient and sustainable solutions. Commercial and industrial clients requiring scalable HVAC systems with minimal environmental impact. Social housing providers aiming to reduce energy costs and carbon footprints in housing projects. Government and municipalities implementing sustainable infrastructure in public buildings. **End of Life** Incentivise product returns for refurbishment or remanufacturing. Integrate circular inputs into new production. Reuse parts and repurpose working components. The product can be stripped down for recycling at last.
Cost Structure & Additional Costs		**Subsidisation**	**Revenue & Sustainability Premium**	
Manufacturing and materials: costs associated with producing high-quality, sustainable products. Service delivery: expenses related to maintenance, upgrades, customer support, and reverse logistics. Research and development: investing in research and sustainable innovations and technologies. Digital infrastructure: developing and maintaining smart platforms and tools.		Government grants for low-carbon solutions, such as UK heat pump grants & Zero-rate VAT currently in place until March 2027 for low-carbon & energy-saving products.	Traditional product sales of HVAC systems and components. Income from maintenance and upgrade services contracts. Recurring revenue from leasing & product-as-a-service offerings. Revenue from smart system subscriptions and energy management tools. Incentives from the government, such as grants or fiscal incentives, enhance decarbonisation efforts. Client advantage of no CapEx costs for installing HVAC systems in a leasing or product-as-a-service model.	

5 Discussion

The four case studies show that HVAC manufacturers increasingly recognise CBM as a strategic pathway to reduce environmental impact while meeting rising demand for low-carbon heating, ventilation, and cooling. Despite differences in product focus and geography, all companies demonstrate practices aligned with major CBM archetypes, indicating that circularity is both feasible and adaptable across the sector. A central theme is the importance of product life extension and resource recovery, especially for high-impact components such as pumps, compressors, and refrigerants.

Initiatives like L∞P by Daikin programme and Grundfos' EU-wide take-back scheme illustrate how reverse logistics and remanufacturing reduce landfill waste and virgin material consumption. Worcester Bosch's recovery of rare-earth magnets further highlights how inter-organisational partnerships unlock material circularity where conventional recycling is insufficient. The PaaS models adopted by Daikin and Kaer demonstrate how shifting from ownership to service provision enables manufacturers to maintain lifecycle control, improving maintenance, recovery, and reducing premature disposal, positioning servitisation as the key strategy for long-term HVAC decarbonisation.

The developed CBM using the SBMC and insights extrapolated from the case studies emphasises sustainable value creation through modular product design, closed-loop supply chains, and digital technologies such as IoT monitoring, predictive maintenance, and energy-management platforms. It also identifies how servitisation supports recurring revenue streams, from leasing, subscriptions, maintenance contracts, and digital services, while reducing resource use. Vital strategies for end-of-life management are also outlined, ensuring that the products, materials and resources can be effectively retained within the value chain over time.

However, the SBMC acknowledges challenges, including higher operational costs for reverse logistics, digital infrastructure, and continuous service delivery. These may be offset by government grants, efficiency gains, avoiding disposal costs, and reduced material extraction, but significant upfront investment and differences in customer acceptance of leasing or PaaS models remain key barriers. Ultimately, raising the cost of product disposal via landfill represents a quick win for governments seeking to promote such business models.

Overall, circular business models offer the HVAC industry substantial opportunities to reduce resource dependency, lower carbon emissions, and create new value. Combining material recovery, circular design, remanufacturing, and service-based approaches provides a robust roadmap for sustainable industry transition.

6 Conclusion

This study examined how HVAC manufacturers can transition from linear business models toward circular economy approaches to address growing environmental and resource challenges within the HVAC sector. By analysing the circular practices of four leading organisations, Grundfos, Worcester Bosch, Daikin, and Kaer, the research demonstrates that CBM is viable and emerging across diverse contexts within the industry. The

cases collectively highlight clear opportunities to reduce resource dependency, minimise waste, and decrease carbon emissions through strategies such as product modularity, remanufacturing, take-back schemes, digital capabilities, and servitisation.

The CBM developed using the SBMC outlines unique approaches that leverage supply chain partners, digital technology, government incentives and policies, revenue streams, and customer relationships to drive sustainability. The SBMC offers a holistic blueprint for manufacturers seeking to operationalise circularity in a structured, strategic, and scalable way. As global sustainability pressures intensify, circularity will become not only an environmental imperative but a competitive differentiator, positioning HVAC companies to meet future energy, climate, and resource challenges with resilience and innovation. Further research should integrate industry insights to enhance the SBMC for enabling the transition of the HVAC sector to circular business models.

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Business Model Innovation for Circular Transformation in the Built Environment

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Abstract. The construction sector is one of the most resource-intensive industries in Europe, accounting for approximately 50% of all extracted materials and generating close to 35% of the EU's total waste output. Despite this scale, Europe's circular material use rate remains low at 11.8%, reflecting the systemic linearity of current production and consumption patterns. Construction and demolition waste records a high nominal recovery rate of around 89% across the EU; however, recent studies show that most recovered material is downcycled into lower-grade applications, rather than reused at high value. This paper investigates how business model innovation can accelerate the change toward a circular built environment by aligning economic incentives with material reuse, long-life design, and digital traceability. Through a structured review of empirical studies and policy analyses, we identify enabling mechanisms such as circular procurement, digital material passports, market platforms for secondary materials, and performance-based contracting. Main barriers include fragmented value chains, limited standardization for reusable components, and insufficient financial drivers for high-value recovery. Policy instruments, including green public procurement, life-cycle costing provisions, digital product information requirements, and construction and demolition waste regulation, are examined as mechanisms that can create demand, improve traceability, and support higher-value recovery paths.

Keywords: Pathways for systemic solutions · Innovative Value Creation · Construction Sector · Circular Construction

1 Introduction

The European built environment is framed as a "systems sector" for resource security and circularity. Official EU communication highlights that buildings and construction require vast resources and account for about 50% of all extracted material, while the construction sector generates over 35% of EU total waste [1]. These magnitudes explain why circular strategies in construction are treated not only as environmental policy, but also as industrial competitiveness policy, particularly when secondary materials can substitute primary extraction. However, economy-wide circularity remains low. Eurostat reports

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that 11.8% of materials used in the EU in 2023 came from recycled materials [2]. The European Environment Agency (EEA) reports that the EU target is to double recycled material use between 2020 and 2030 to reach 22.4% by 2030, with a stated ambition "even slightly increased" to 24% [3]. The gap between current performance and targets suggests that incremental improvements (higher recycling rates without quality assurance) will not be sufficient. Construction and demolition waste (CDW) reveals a crucial paradox. The Joint Research Centre (JRC) reports that CDW accounts for almost 40% of all waste generated in the EU [4]. Reported recovery performance is high: for 2020, JRC indicates an EU average CDW recovery rate of 89%, ranging from 63% (Finland) to 99% (Luxembourg) [4]. Yet JRC cautions that such recovery often produces low-quality recycled aggregates for backfilling or road sub-bases; and EU-reported shares for the mineral fraction show "preparing for reuse" at 0%, with recycling/backfilling/landfilling averaging 79% / 10% / 11% [4]. In other words, current systems prioritize mass diversion over value retention. That is a business-model problem as much as a technical problem: actors capture value from primary supply and project throughput, while reuse markets face information asymmetries, liability risk and fragmented demand.

This paper addresses the following research questions:

RQ1: Which circular business model archetypes are most actionable for buildings and renovation within current EU policy trajectories?
RQ2: What actor-specific barriers limit high-value reuse and recovery (beyond nominal "recovery rates")?
RQ3: Which EU policy levers (waste, product, procurement) offer quantifiable signals and practical mechanisms to unlock circular business models?

Our contribution is a synthesis that links (1) business model innovation theory and circular business model archetypes, (2) the empirically observed "quantity-quality" gap in CDW management, and (3) policy levers that change economics via data infrastructure, procurement demand and standardization. Unlike previous reviews that mainly classify circular construction barriers, procurement barriers, or circular business model typologies separately, this paper integrates these three evidence streams into a single policy-ready framework.

2 Literature Review

Circular economy strategies require simultaneous change in product/service design and in "value creation-delivery-capture" logics. A widely cited foundation differentiates strategies that narrow, slow, and close resource loops, reducing resource intensity, extending product life, and cycling materials back into production [5]. For buildings, analogues include (a) reducing virgin inputs through design efficiency and secondary materials, (b) extending service life through adaptable layouts and performance-based maintenance, and (c) closing loops through reuse, remanufacture and high-quality recycling.

Circular business models in the literature are often grouped into a limited number of "families". A review of circular business models synthesizes core modes such as cycling materials, extending product life, intensifying use (sharing), and dematerializing through service substitution [6]. Circular Business Model Canvas extensions add take-back systems and adoption factors relevant to construction products [7]. Sector-specific

evidence nevertheless shows persistent barriers. A systematic review of circular economy in the construction industry (covering 45 studies) identifies recurring constraints including higher upfront costs, tight schedules, limited awareness/regulatory clarity, and path dependence in current supply chains [7, 8]. Complementarily, a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-based systematic review of circular procurement in construction (covering 46 studies) classifies both "hard" barriers (lack of design-for-reuse, reverse logistics, information management, standardization) and "soft" barriers (limited trust, weak collaboration, resistance to change) [9]. Reviews focused on green public procurement in construction further stress the need to operationalize environmental criteria and performance monitoring across procurement practice [10].

Circular construction depends on practical standardization: classification of reused components, test regimes, interfaces, and contractual allocation of liability. Research argues that circular reuse is constrained by limited standardization and fragmented assurance methods; standardization trajectories (including ISO approaches to disassembly and adaptability) can lower transaction costs and reduce risk, enabling wider reuse markets [11]. These insights align strongly with the JRC observation that reported high recovery rates may mask poor circularity due to low-value pathways and limited high-grade reuse [4]. A main theme across the literature is that market transformation is unlikely without policy levers that shape demand and reduce uncertainty. Two policy mechanisms stand out for buildings: waste policy (targets and definitions that affect reporting and incentives) and procurement (creating demand and rewarding life-cycle outcomes). Procurement is also a major demand-side lever: the OECD reports that government procurement accounts for around 13% of GDP on average in OECD countries [12]. This scale makes circular procurement and life-cycle costing important mechanisms for moving circular construction from pilots to market practice.

3 Methodology

This study applied a mixed-method evidence synthesis combining a structured umbrella review with policy mapping. The umbrella-review component synthesized academic evidence on circular business model archetypes, barriers, and enabling mechanisms in the built environment. The policy-mapping component examined how EU policy instruments create conditions for implementation through material-flow regulation, information infrastructure, demand formation, and assurance. The review focused on sources published between 2015 and 2026 and used combinations of the terms "circular construction", "circular economy", "business model", "circular procurement", "green public procurement", "construction and demolition waste", "reuse", "deconstruction", "digital product passport", and "standardization". Priority was given to systematic reviews, PRISMA-based reviews [13], umbrella reviews, major conceptual papers, and high-authority institutional sources containing quantified indicators or regulatory evidence. Inclusion criteria were relevance to buildings, renovation, construction products, CDW, public procurement, or secondary material markets. Opinion pieces and sources without traceable relevance to business models, barriers, enabling conditions, or policy instruments were excluded. Barriers were coded and qualitatively weighted using three criteria:

frequency in the reviewed evidence, implementation severity, and cross-actor relevance. Barriers were classified as high priority when they were repeatedly identified and directly prevented circular business models from functioning, for example by blocking reuse, increasing liability risk, weakening procurement uptake, or limiting secondary material markets. Medium-priority barriers were more context-dependent, such as limited awareness, resistance to change, or higher upfront costs.

Enabling mechanisms were derived through thematic synthesis. Repeated comparison of the reviewed barriers, business model requirements, and policy instruments produced three enabling domains: information and traceability infrastructure, demand formation through procurement and life-cycle costing, and assurance through standardization and liability allocation. The policy mapping relied on secondary policy literature, institutional reports, and legal documents, including the Waste Framework Directive [14], the EU Circular Economy Action Plan [15], the Ecodesign for Sustainable Products Regulation [16], the Construction Products Regulation [17], and relevant national implementation sources concerning construction and demolition waste management, public procurement, and circular economy policy [18–20]. The two parts of the study were linked through an evidence matrix. For each business model archetype, the analysis identified the value proposition, revenue and risk logic, dominant barriers, required enabling mechanisms, and relevant policy levers. This synthesis was used to answer research questions by identifying actionable business model archetypes, explaining the barriers that limit high-value reuse and recovery, and mapping the policy levers that can support circular implementation. Because the study relies on secondary evidence, the findings should be interpreted as a structured synthesis rather than empirical validation of business model performance.

4 Results

Table 1 translates circular strategy families and specific construction findings into implementable archetypes. These archetypes are designed to be "policy-ready": each implies specific data, procurement and assurance needs consistent with evidence on barriers [8–11]. Table 1 also represents the evidence matrix linking the literature-derived business model archetypes with the barrier categories, enabling mechanisms and policy levers identified through the mixed-method synthesis.

The most influential barriers were lack of reliable information on component composition and condition, fragmented value chains, limited standardization and certification, weak demand for reused components, and limited use of life-cycle costing. These were treated as high-priority barriers because they appeared repeatedly in the reviewed evidence, directly affected implementation, and involved several actors across the construction value chain. Across the reviewed literature and policy mapping, the enabling mechanisms clustered into three interdependent domains: information and traceability infrastructure, demand formation through procurement and life-cycle costing, and assurance through standardization and liability allocation. These domains represent the main conditions under which circular business models can move from isolated pilots to wider implementation in the built environment.

Table 1. Circular business model archetypes for the built environment

Archetype	Circular value logic	Main barrier addressed	Required enabling mechanism	Relevant policy lever
Component-as-a-Service	Performance-based delivery of building systems such as HVAC, lighting or façades	Short-term procurement and unclear performance responsibility	Outcome-based procurement, life-cycle costing, performance data	GPP, LCC, public procurement
Take-back and remanufacture	Return, refurbishment and reuse of construction products	Weak reverse logistics and unclear end-of-life responsibility	Product identity, take-back clauses, testing	ESPR, CPR, waste policy
Reclaimed components marketplace	Resale of reusable components	Information asymmetry and uncertain quality	Digital inventories, inspection, certification	DPP framework, CPR, standards
Deconstruction and resale services	Higher-value recovery through selective dismantling	Demolition-oriented recovery and low-value backfilling	Pre-demolition audits, selective dismantling, demand aggregation	WFD, CDW regulation, procurement
Building as material bank	Long-term residual value through material inventories	Lack of long-term material information	Material passports and component records	ESPR, CPR, circular economy policy
Space-use intensification	Higher utilization of floor area	Demand for new construction despite underused space	Flexible occupancy models and digital access systems	Urban planning and service procurement
Secondary material supply contracts	Stable supply of quality-assured secondary inputs	Unstable demand and inconsistent quality	Long-term contracts, recycled-content specifications	GPP, LCC, material standards

The first enabling domain is information and traceability infrastructure, because circular business models require reliable data on product composition, component condition, origin, and future reuse potential. Evidence shows that lack of reliable information on component composition, condition and provenance is a major "hard" barrier to circular procurement [9]. EU policy is moving toward digital product information. The ESPR establishes a framework for eco-design requirements and Digital Product Passports to improve availability and usability of product sustainability information [16]. For construction products, CPR updates product marketing rules and digital information requirements, reinforcing data availability across the value chain [17]. While these regulations do not yet provide outcome metrics themselves, they are enablers aimed

at reducing information asymmetry that prevents reuse markets from scaling. The second enabling domain is demand formation through procurement and life-cycle costing, because circular solutions need predictable demand and evaluation criteria that reward long-term value rather than only lowest initial cost. OECD emphasizes that procurement is an economic lever of scale, accounting for around 13% of GDP on average across OECD countries [12]. Within the OECD report methodology, 38 countries responded to the 2022 Green Public Procurement survey [12]. Such scale supports the adoption of outcome-based and life-cycle approaches when contracting authorities require longer warranties, take-back, reusable components, or verified secondary material content.

The third enabling domain is assurance, standardization, and liability allocation, because reused components and secondary materials require trusted quality evidence, clear responsibilities, and accepted technical rules. Systematic reviews highlight that standardization and quality management are central barriers to reuse and circular procurement [9, 11]. Standardization can lower transaction costs, enable compatible interfaces, and reduce liability-based resistance to reused components [11]. JRC evidence that official reporting shows "preparing for reuse" for mineral CDW at 0% suggests that high-grade reuse has not yet become a standardized, reportable and incentivized pathway in practice [4]. Table 2 summarizes policy instruments with quantified signals.

Table 2. Policy instruments and quantified signals relevant to circular business models

Policy signal	Quantified evidence / policy function	Relevance to business models
Circular material use	EU CMUR was 11.8% in 2023; 2030 target is 22.4%, with ambition to reach 24% [2, 3]	Shows underdeveloped secondary material markets
CDW recovery-quality gap	EU CDW recovery averaged 89%, but mineral CDW "preparing for reuse" was reported at 0% [4]	Shows need for high-value reuse models, not only recycling
Waste policy	WFD requires 70% preparing for reuse, recycling or other material recovery of non-hazardous CDW [14]	Creates diversion incentives but needs quality-oriented business models
Digital product information	ESPR and CPR support digital product and construction product information [16, 17]	Enables DPPs, traceability, material banks and reuse markets
Procurement demand	Public procurement represents around 13% of GDP on average in OECD countries [12]	Supports circular procurement, LCC and performance-based contracts

5 Conclusion

This paper directly answers the three research questions stated in the Introduction. For RQ1, the most actionable archetypes are component-as-a-service, take-back and remanufacture, reclaimed-component marketplaces, deconstruction and resale services, buildings as material banks, space-use intensification and secondary material supply contracts. They are actionable because they connect circular value creation with concrete revenue, responsibility and data mechanisms. For RQ2, high-value reuse and recovery are mainly constrained by unreliable component information, fragmented value chains, limited standardization and certification, unclear liability, weak demand for reused components and insufficient life-cycle costing. These barriers explain why high CDW recovery rates can still mask downcycling and low-value recovery. For RQ3, waste regulation, green public procurement, life-cycle costing, digital product information requirements and construction product regulation are the most relevant levers because they create demand, improve traceability and provide assurance for reused components and secondary materials. Therefore, circular construction should start with practical market conditions: public authorities can require circular procurement criteria and traceable product information, while firms can develop take-back agreements, reusable-component inventories and quality-assured secondary material supply chains. The study is limited by reliance on secondary evidence; future research should test the framework through case studies, procurement pilots and actor-level data.

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Circular and Sustainable Tourism as a Driver for a Resilient Built Environment

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Abstract. Tourism systems have a significant impact on the sustainability of the built environment. This article presents the results of an assessment of resources and processes for implementing the principles of the circular economy and the Green Deal in the Tourism System (CirToS) – a functional circular economy model developed to support the methodological application of sustainable development and circular economy principles in tourism at both enterprise and regional levels. The model is based upon four interrelated dimensions: Culture, Society, Environment, and Governance, and follows a functional logic linking inputs, processes, and outputs. The model integrates qualitative and quantitative self-assessment from the company perspective, enabling tourism stakeholders to evaluate the maturity level of their circular economy and sustainable practices through a structured multi-level assessment scale. Emphasis is placed on integrating cultural and natural heritage, community engagement, environmentally responsible infrastructure and mobility solutions, and governance mechanisms supported by digital monitoring tools into the broad and complex built environment framework. Validation of the model was conducted using a sample of regional companies representing different tourism sub-sectors, followed by expert-based assessments that enabled iterative refinement, calibration, and benchmarking of the results. The findings demonstrate the model's capacity to identify improvement pathways, support relative decoupling of economic performance from environmental impact, and promote more efficient, multiple-cycle use of built assets. The developed model provides a practical decision-support tool for tourism enterprises, planners, and policymakers seeking to enhance resilient built environments through circular and sustainable tourism development.

Keywords: Circular Economy · Decision-support Model · Resilient Built Environment · Tourism Systems

1 Introduction

Although the circular economy is increasingly recognised as an important pathway towards sustainable tourism, academic research on its application in tourism systems remains relatively limited [1–3]. At the same time, growing policy attention to circular economy principles, particularly within the European Green Deal and the Circular

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Economy Action Plan, has stimulated increasing interest in this topic among tourism researchers [4–6].

Recent studies emphasise the importance of measurable indicators and assessment tools for evaluating circular economy implementation at both organisational and territorial levels. The Circular Economy Index, for instance, proposes a methodology for assessing circularity in municipalities through a structured indicator system that links the environmental, economic, and governance dimensions of the circular transition [7–9]. Such approaches demonstrate the need for practical decision-support models that allow organisations and regions to monitor their progress towards circular economy objectives.

To address this need, the proposed CirToS functional model is structured around four interrelated dimensions: Culture, Society, Environment, and Governance, and follows a functional logic linking inputs (resources and contextual conditions), processes (organisational and sectoral practices), and outputs (measurable effects and performance indicators).

2 Materials and Methods

The current study applies a mixed-methods approach to develop and validate a functional assessment model for circular and sustainable tourism practices. The methodology outlines a logic model that connects inputs (resources, conditions, and capacities), processes (organisational practices), and outputs (measurable performance indicators), which allows linking indicators, baselines, and verification metadata to support monitoring, learning, and management. The developed methodology is aligned with the ISO 59000 family standards [10], including ISO 59004:2024 circular economy principles and their implementation, ISO 59010:2024 on organisational transition perspective, and ISO 59020:2024 on indicators for measuring circularity performance.

The model is developed based on four dimensions: Culture, Society, Environment and Governance, aligning sustainable tourism practices with governance-focused standards that view sustainability as a systemic quality. Moreover, it is based on evidence that urban areas are complex systems where it is essential to keep buildings, components, and materials in use as long as possible through reuse, renovation, and end-of-life planning. This approach helps reduce negative impacts and boost resilience. The approach is in line with existing best practices and guidelines [11, 12].

The model development follows a three-stage process: conceptualisation, development, and validation [13]. This process reflects the current practices in circular economy readiness frameworks. First, the authors developed an initial pool of indicators identified in the literature and grouped them thematically based on their conceptual similarity and relevance to tourism system circularity. This process resulted in the identification of four interrelated dimensions (Culture, Society, Environment and Governance) and the development of a structured indicator catalogue comprising 49 assessment variables. Second, the authors converted the items into a structured self-assessment questionnaire with 49 variables. This responds to the previous findings that questionnaire-based circularity tools can be useful when they prioritise quantitative indicators when possible [14]. The questionnaire survey was conducted among tourism enterprises operating within the project target region. The study population consisted of approximately 350 tourism-related enterprises identified through business registers. Based on this population size,

the required minimum sample size was calculated as 21 responses using a 90% confidence level, a 5% margin of error and an assumed population proportion of 98%. A total of 27 responses were collected, of which 24 were considered valid and included in the analysis. In total, 27 questionnaire responses from tourism companies were collected, of which 24 were considered valid and included in the analysis. On the third stage, the authors plan to use a multi-level maturity scale for each assessment area to aid in benchmarking and improvement planning [15]. The full results of the second and third stages will be described in the coming papers.

3 Results and Discussion

The CirToS functional model is designed to assess and promote the implementation of sustainable and circular economy principles in the tourism sector. The model offers a systemic approach that includes four dimensions: Culture, Society, Environment and Governance. Together, these dimensions form an integrated framework for action at the company and sector level. The purpose of the developed model is to provide both a qualitative and quantitative basis for self- assessment to determine the level of readiness of the organisation to implement circularity and sustainability. It is recommended to conduct a self-assessment once a year, involving the company's management and at least one employee from each structural unit. The self-assessment process emphasises discussion, joint learning and cross-sectoral cooperation.

The model is a functional system that links inputs (resources and context), processes (practical actions implemented by the organisation or sector), and results (obtained effects, indicators and changes). Each pillar is at the same time independent and mutually complementary, ensuring a holistic view of sustainability. The model can be applied at two levels:

1. at the company level to identify the organisation's sustainability practices and potential for improvement;
2. at the sector or region level to assess the overall system's ability to implement circular principles in the tourism sector.

The checklist is structured according to the CirToS dimensions. Each dimension includes the main practice areas in which organisations can assess their current performance, marking either implemented or improvements needed. This section is applicable to both the company and the sector context. Table 1 presents the four dimensions of the CirToS model together with their respective assessment areas and indicator categories.

The authors proposed the following validation guidelines (qualitative self-assessment). The self-assessment is based on a qualitative approach, which involves discussion and evidence gathering for each CirToS dimension. Organisations are invited to assess not only current practice but also the potential for development.

The self-assessment process includes the following stages:

1. Preparation: identification of participants and data.
2. Discussion: group work with a checklist and exchange of examples of good practice.
3. Evidence gathering: documents, data, photos, interviews.
4. Analysis and interpretation: identification of strengths and areas for improvement.

Table 1. Dimensions of the functional model

CirToS dimension	Assessment areas	Main evidence / data points
Culture	Cultural heritage; Intangible culture; Nature conservation	Heritage integration into tourism offers; cooperation with local artisans and cultural organisations; inclusion of traditions, stories and food; biodiversity and natural heritage protection
Society	Engagement; Education; Accessibility	Resident participation in tourism planning; cooperation with schools, NGOs and communities; sustainability education for tourists and employees; inclusive and accessible services
Environment	Waste; Energy; Transport; Water	Waste sorting and resource reuse; food loss reduction; energy monitoring and efficiency measures; green mobility solutions; water conservation practices
Governance	Strategy; Digitalisation; Financial governance; Projects	ESG or sustainability strategy; digital tools for monitoring indicators; financially responsible management linked to sustainability; realised projects and collaborative partnerships

Source: Developed by the authors based on the study data, with visual assistance from OpenAI ChatGPT; final content reviewed and edited by the authors.

5. Feedback and validation: presentation of results and comparison with other companies or regions.

To complement the qualitative self-assessment, a quantitative approach can be used, for example, by assigning points or ratings on a five-level scale for each criterion. This approach allows for the analysis of progress over time and comparisons between organisations or regions. Recommended five-level scale:

1. Not implemented
2. In the planning stage
3. Partially implemented
4. Well implemented
5. Fully integrated into organisational practice

The five-level scale is interpreted as follows: 1 - No policy or activity plan; 2 - An idea is being developed, but it is not documented; 3 - Some activities are taking place (specify %); 4 - The action plan is documented (specify where), is implemented regularly (frequency, volume); 5 - Systemic, data-driven approach (multi-period cycle; activities are aligned with the company strategy).

Quantitative assessment can be combined with indicators, such as: reduction in energy consumption (%), waste reduction (kg), proportion of local suppliers (%), or number of public participation activities. These data provide a basis for long-term monitoring and policy planning.

Based on the in-depth research, the authors have also developed a visual representation of the model, which is depicted in the Fig. 1 below.

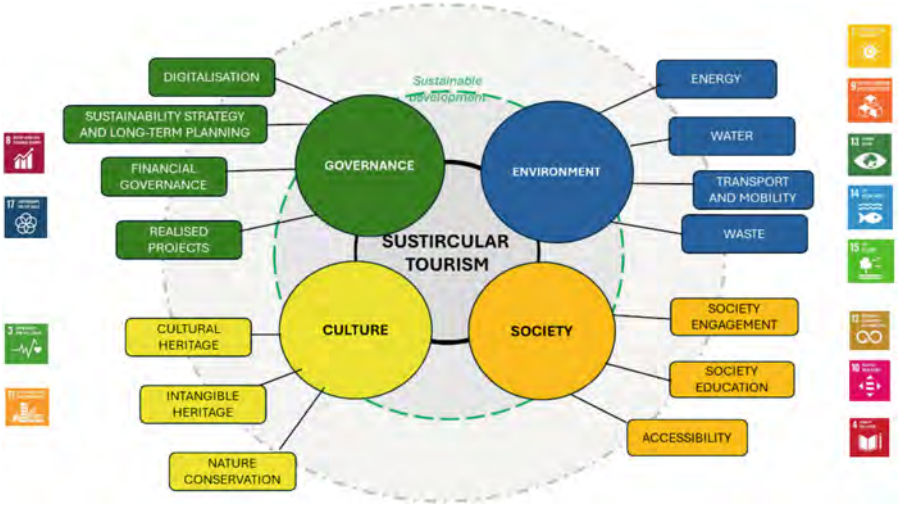


Fig. 1. The CirToS functional model. Source: developed by the authors

Within the conceptual model, the authors have identified a new term, "Susticular" tourism, which comprises an integrated sustainable and circular tourism approach that empowers local communities, preserves natural and cultural heritage, focuses on resource efficiency and supports a resilient tourism system by applying responsible governance and circular resource loops. Overall, emerging both from Table 1 and Fig. 1, the model suggests that nowadays tourism needs to be assessed not only through an environmental prism, but through four main pillars: culture, society, environment and governance. Culture is part of circular value, as local identity traditions, stories, food, and heritage buildings can be preserved, reused, and reactivated through tourism. Society focuses on people, meaning that tourism development should involve local communities, create social value, and remain accessible and inclusive, with this leading to sustainable development of the region. Environment is the most direct circular economy part of the model, because it focuses on reducing resource use, reusing materials, cutting waste, and supporting greener mobility. Governance connects the dimensions through strategy, digitalisation, financial governance, and realised projects. This dimension makes the model operational by turning values into management practices. In general the model shows that resilient tourism is created when heritage and community value are combined with efficient resource use and strong governance.

Spearman's rank correlation analysis was performed using the 24 valid questionnaire responses. Each respondent evaluated the implementation level of practices within the four CirToS dimensions using a five-level maturity scale. Composite scores were calculated for each dimension and correlated with the overall self-assessment score. The analysis revealed that Society ($\rho = 0.833$) and Governance ($\rho = 0.828$) are the strongest predictors of the overall assessment score, suggesting that community engagement and

ESG governance frameworks are the primary drivers of circular tourism readiness. Culture/Heritage ($\rho = 0.787$) also demonstrates a strong association, underscoring its role as an integral component of sustainability transitions. By contrast, Environment ($\rho = 0.458$) shows the weakest correlation, indicating that while environmental practices are present, they remain insufficient in depth and integration to significantly differentiate overall performance. The initial application of the CirToS framework also indicates that the level of circular economy readiness differs significantly across tourism sub-sectors. Sectors with higher infrastructure intensity, such as accommodation and event management, demonstrate stronger implementation of environmental and governance practices, while smaller operators in cultural and activity-based tourism tend to remain at earlier stages of circular transition. The self-assessment results further indicate that small and medium-sized tourism enterprises face structural barriers in implementing circular practices, particularly related to financial capacity, documented governance, availability of sustainability data, and managerial expertise. These findings confirm that targeted policy instruments and sector-specific support mechanisms are necessary to facilitate the implementation of circular economy principles and the objectives of the European Green Deal within the tourism system.

To extend the applicability of the CirToS functional model, future validations could integrate tracking of key performance indicators, such as percentage reductions in energy intensity per guest-night, increases in local sourcing ratios enabling tourism businesses to compare their progress to regional standards over time through repeated checks. This ongoing monitoring could demonstrate how circular steps, for instance, reusing existing heritage buildings for eco-friendly stays or establishing shared transport hubs to cut car use, can enhance the resilience of the built environment by cutting the need for new construction and maximising use of existing structures. Also, linking the model's governance part with digital twins (virtual copies of tourism sites) could test "what-if" scenarios, such as upgrading event spaces for zero waste. Such advancements would empower smaller operators to overcome structural barriers through accessible technology integrations, supporting scalable approaches where preserving cultural heritage also acts as a circular resource cycle in Latvia's tourism.

4 Conclusions

Circularity in tourism cannot be achieved through isolated company actions but requires coordinated system-level transformation across the tourism value chain. The CirToS model developed within this research demonstrates that such a transformation requires the integration of cultural, social, environmental and governance dimensions within tourism management and planning processes - something that has not been the clear focus of policy planners and regional development institutions from this angle of assessment. The authors have identified and validated the thesis that circular tourism practices significantly influence the resilience of the built environment by promoting adaptive reuse of existing infrastructure, reducing resource throughput and improving spatial planning of tourism services. The application of the model through qualitative self-assessment and indicator-based evaluation enables tourism industry stakeholders, regardless of their size, to identify their level of readiness for implementing circular economy principles

and sustainability practices. In summary, it can be highlighted that the CirToS functional model provides a practical framework for integrating circular economy principles into the tourism system. The results also highlight the importance of cooperation between tourism stakeholders, destination managers and public authorities in facilitating the transition towards circular tourism aligned with the objectives of the European Green Deal. By linking cultural, social, environmental and governance dimensions with measurable indicators and maturity assessment tools, the model supports tourism enterprises and policymakers in identifying pathways towards resilient and resource-efficient tourism development. The results demonstrate that circular tourism has the potential to strengthen the sustainability of the built environment while contributing to the broader objectives of the European Green Deal. Further research should focus on refining the indicator system for monitoring circularity performance at the company and regional levels.

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Early-Stage Financial Risk Assessment of Energy Retrofit Strategies for Net-Zero Residential Buildings

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Abstract. The built environment accounts for a significant share of global energy consumption and carbon emissions, underscoring the urgent need for effective strategies to achieve net-zero targets. Energy-efficiency retrofitting has emerged as a critical approach to enhancing the performance of existing residential buildings. However, the adoption of retrofit measures is often limited by financial uncertainties and investment risks. This study conducts a systematic literature review to analyze financial evaluation methods and risk factors related to energy retrofit strategies for net-zero residential buildings

This review summarizes commonly employed financial evaluation techniques, including hedonic pricing analysis, Monte Carlo simulation, Life Cycle Cost Analysis (LCCA), and Cost-Benefit Analysis (CBA). The findings indicate that financial risks-such as high upfront investment costs, uncertain energy prices, and extended payback periods-substantially influence decision-making. Despite these risks, deterministic financial assessment methods, particularly LCCA, remain predominant in retrofit investment analysis. The results emphasize the importance of integrating financial risk considerations early in the retrofit planning process to facilitate more informed investment decisions. This study offers insights to refine financial evaluation procedures in residential retrofit projects and enhances understanding of the financial factors influencing energy retrofit adoption.

Keywords: Energy Retrofit · Financial Risk Assessment · Net-Zero Residential Buildings · Financial Evaluation · Early-Stage Decision Making

1 Introduction

1.1 Background of Energy Retrofit and Net-Zero Buildings

Buildings, particularly residential ones, account for a substantial share of global energy consumption and carbon emissions [1]. Urban expansion is projected to increase energy demand from residential buildings, thereby exacerbating pressure on energy resources and the environment [2]. Many existing structures were built before modern energy-efficiency standards were implemented [3]. Consequently, governments, policymakers, and the construction sector prioritize improving the energy performance of these

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older buildings. Energy retrofit methods are commonly used to improve the energy efficiency of existing buildings [4, 5]. These methods involve upgrading systems such as lighting, heating, and cooling, as well as installing renewable energy technologies to reduce energy consumption and costs [4]. Recently, net-zero energy buildings (NZEBs) have become a prominent strategy to reduce environmental impacts. NZEBs combine energy-efficient design with renewable energy generation to achieve energy balance over time [6]. Improving the energy performance of older residential buildings through retrofitting can significantly reduce energy demand and greenhouse gas emissions, advancing international sustainability objectives.

1.2 Financial Challenges in Energy Retrofit Projects

Financial difficulties remain a significant obstacle to the widespread adoption of energy retrofit strategies, despite their environmental and operational benefits [7]. Upgrading building systems and technologies requires a large initial investment, which is one of the biggest obstacles to energy retrofit projects [8, 9]. Building owners and investors may be deterred from implementing energy efficiency improvements by the high upfront costs associated with many retrofit measures [10]. Uncertainties about energy savings and future energy prices can complicate investment decisions, along with high initial costs. Long-term energy cost savings, which can fluctuate with changes in energy prices and building performance, are a major factor in the financial performance of retrofit projects [11]. Consequently, building owners and investors might view retrofit investments as financially hazardous.

1.3 Research Gap, Aim and Objectives

The economic and environmental advantages of energy retrofit strategies have been examined in past studies, but the financial risks that affect investment decisions in retrofit projects have received less attention. Financial evaluation techniques, including Life Cycle Cost Analysis and Cost-Benefit Analysis, are frequently used in current research, but they don't always adequately account for cost uncertainty, energy savings, and long-term returns. This creates a research gap regarding how financial risk influences the choice of retrofit techniques for net-zero residential buildings. In this regard, this paper reviews methods for assessing the financial risks of net-zero energy retrofitting in residential buildings. Its aims include determining the most widely used financial assessment tools in the context of retrofit research and studies on the most significant financial risk aspects in investment decision-making, and the role of financial concerns in implementing a retrofit strategy for residential structures.

2 Literature Review

2.1 Financial Evaluation Methods for Energy Retrofit Projects

Financial analysis is a significant tool for assessing the viability of energy retrofit projects [12]. Several financial analysis techniques have been extensively used in prior studies to assess the economic performance of retrofit investments. A commonly used approach

is the Life Cycle Cost Analysis (LCCA), which considers the overall cost of a building or retrofit project over its entire life span, including initial investment, operational, maintenance, and replacement costs.

The other common method is Cost-Benefit Analysis (CBA), which compares the economic benefits of retrofit measures with their costs. This is one way to enable decision-makers to understand whether the financial payback from energy savings warrants the initial outlay required to implement the retrofit. Additionally, other studies have used Monte Carlo simulations to address uncertainties in financial evaluations. Hedonic pricing has also been applied to analyze the economic outcomes of green buildings by examining the correlation between building characteristics and market value, encompassing premiums in rental and property prices.

2.2 Financial Risk Factors in Energy Retrofit Investments

Even with the potential advantages of energy retrofit approaches, financial risk remains a significant impediment to their implementation [2]. According to Jafari and Valentin [13], the initial high upfront investment cost in retrofit projects is one of the most recognized monetary challenges. Furthermore, Shen, Braham, Yi and Eaton [14] emphasized that, most energy efficiency measures require a high initial investment, which might dishearten building owners and investors from exploring retrofit programs. Uncertainty concerning energy prices and energy savings is also a significant financial risk factor [13, 15, 16]. The expected decrease in energy costs with time is likely to determine the financial feasibility of retrofit projects [14]. Nevertheless, the performance of the buildings can affect the validity of projected savings due to variability in energy prices and changing performance, introducing uncertainty into financial analyses [17–20].

Long payback periods are also an important challenge for retrofit investments [21–24]. The period of cost recovery can take several years, though the energy-saving technologies can provide long-term cost savings [25–27]. Also, Prabatha, Hewage, Karunathilake and Sadiq [16] stated that investors may be uncertain about the profitability of such investments or whether the market will demand energy-efficient buildings; hence, this could also affect the financial aspects of decision-making in retrofit projects.

3 Research Methodology

3.1 Systematic Literature Review (SLR) Approach

The paper follows a systematic literature review (SLR) to examine financial risk assessment tools used in energy retrofit strategies for residential buildings. A systematic literature review enables researchers to identify, evaluate, and synthesize existing research. The SLR approach follows a predetermined procedure, unlike the standard narrative review, thereby increasing the reliability and reproducibility of the research process.

3.2 Search Strategy and Data Source

The Scopus database was used for literature research; The choice of Scopus was due to its extensive selection of high-quality journals used in building retrofit and energy efficiency

research. Relevant studies were identified using a structured keyword search strategy, and articles published during 2015- 2025 were selected. The keywords were combined using Boolean operators to ensure sufficient coverage of the relevant publications. The search string used in the Scopus database was: (“energy retrofit” OR “building retrofit" OR "deep retrofit”) AND (“financial evaluation” OR “life cycle cost” OR “cost-benefit analysis”) AND (“net zero building" OR "energy efficiency” Fig. 1)

3.3 Study Selection Process (PRISMA)

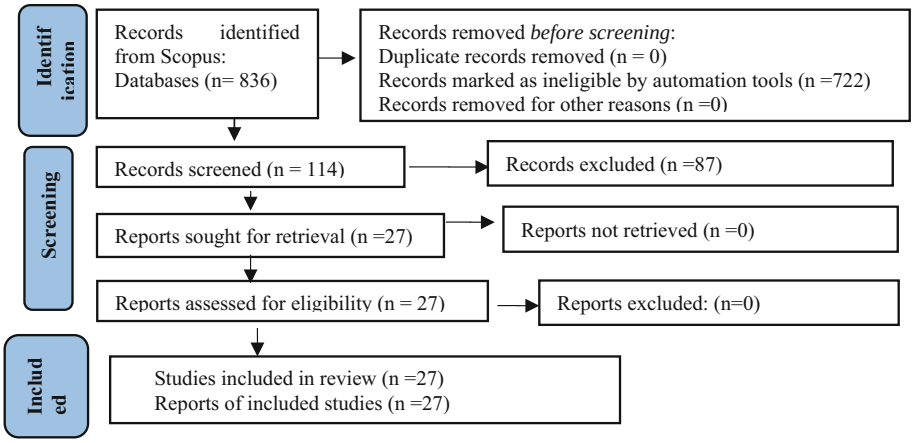


Fig. 1. PRISMA flow diagram illustrating the study selection process used in the systematic literature review

3.4 Inclusion and Exclusion Criteria

Inclusion and exclusion criteria were used to screen the studies and select relevant, high-quality studies.

The inclusion criteria required that the selected studies were peer-reviewed journal articles, were published in English, addressed energy retrofit or building energy efficiency and included financial evaluation or financial risk considerations.

Studies were excluded if they were not related to building retrofit or energy efficiency, did not include financial evaluation or economic analysis, were conference abstracts, editorials, or non-academic publications.

The residential and commercial building studies were considered relevant because they provide valuable insights into the financial evaluation methods used in retrofit projects.

4 Results and Findings

4.1 Distribution of Studies

The chosen articles can be regarded as indicative of a broad geographic focus, as they represent the world's interest in energy retrofit methods and their economic consequences. A large proportion of the analyzed studies were conducted in developed nations, especially the United States, the United Kingdom, Australia, and several European nations such as Italy, Spain, and Finland. Besides that, some studies were conducted in the Asian markets such as China, Singapore, Malaysia and South Korea. This distribution shows growing international interest in improving building energy performance and evaluating the economic viability of retrofit projects.

Most studies primarily focused on residential buildings due to their substantial share of global energy consumption. However, some research also examined commercial buildings, including office and green-certified structures, to evaluate financial performance and investment outcomes. Findings suggest that financial assessment tools used in retrofit research are applicable across various building types, with a greater emphasis on residential retrofit projects, given their potential to reduce energy consumption and carbon dioxide emissions.

4.2 Financial Evaluation Methods

Since the chosen studies focus on the economic viability of energy retrofit projects, it can be concluded that a range of financial analysis tools is typically used to assess it. The most popular of these techniques is Life Cycle Cost Analysis (LCCA). LCCA considers the total cost of retrofit measures over the building's lifetime, including initial investment, operational, maintenance, and replacement costs. This approach is also common as it creates a detailed overview of the financial performance of retrofit investments over time.

Another commonly used method is Cost-Benefit Analysis (CBA), which calculates the economic value of energy savings relative to investment costs. CBA is often combined with LCCA to offer a more detailed financial evaluation of retrofit strategies.

Monte Carlo simulation is employed in several studies to address uncertainty in financial evaluations by modelling variations in energy prices, discount rates, and estimated energy savings. Additionally, hedonic pricing analysis has been applied to investigate how energy-efficient or green-certified buildings influence market value, including rental premiums and property prices. Overall, findings indicate that deterministic financial assessment methods, particularly LCCA, remain dominant in retrofit investment analysis.

4.3 Financial Risk Factors

The review has identified several major financial risks that determine the adoption of energy retrofit strategies. A high initial investment cost of retrofit measures is one of the most reported challenges. Retrofit projects are often associated with high initial capital investments by building owners and investors, which can put off many who may not embrace energy-saving technologies and building upgrades.

Uncertainty about energy cost, as well as projected energy savings, is another significant risk factor. Retrofit projects are mostly viable for long-term reductions in energy costs. But changes in energy prices and building performance may create uncertainty in financial projections.

There are also long payback periods that are generally cited as a hindrance to retrofit investment. Even though energy-saving technologies can yield long-term operational savings, the period required to recoup the investment may take years. Other financial risks reported in the literature include the uncertainty about returns on investment and the energy-efficient property market.

4.4 Interpretation and Implications

The results of this review indicate that financial risk factors are vital to the decision-making process for energy retrofit. Although several financial appraisal procedures are employed in the evaluation of retrofit investments, most of the literature on the subject utilizes deterministic cost analysis techniques, such as Life Cycle Cost Analysis. Such methods do not necessarily account for uncertainties in energy prices, building performance, and long-term economic conditions.

The findings show that financial risk assessment in the initial phases of retrofit planning is critical for improving investment decision-making. Stakeholders may improve their understanding of potential risks and financial variability by using advanced financial analysis tools, such as probabilistic modelling methods, such as Monte Carlo simulation.

In practical terms, the results indicate that establishing systematic financial risk assessment schemes would be valuable for retrofit investment decision-making. Financial incentives, subsidies, and policy mechanisms would also help motivate decision-makers to reduce investment risks and adopt energy retrofit strategies in residential buildings.

5 Conclusion

The paper has reviewed methods for assessing financial risks used in the analysis of net-zero retrofit residential buildings, based on a systematic literature review. The findings show that some available financial evaluation techniques, such as Life Cycle Cost Analysis, Cost–Benefit Analysis, Monte Carlo simulation, and hedonic pricing analysis, are widely used in retrofit investment studies. Life Cycle Cost Analysis is the most common method for evaluating long-term monetary performance. The review also found that several other important financial risk factors affected the adoption of retrofit, including high upfront investment costs, uncertainty in energy prices and projected energy savings, and long payback periods. These risks are very important in investment decision-making and even limit the extensive deployment of retrofit strategies.

The results show the importance of including financial risk evaluation in the initial phases of retrofit planning to facilitate more well-informed decision-making. Nevertheless, research has its limitations, such as reliance on a single academic database and peer-reviewed journal articles. Future research can broaden the scope of the analysis by incorporating additional databases and empirical studies of real retrofit projects. It

is also possible to conduct additional research on advanced financial modelling and decision-support tools to enhance the performance of retrofit investment assessment under unstable economic conditions.

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Enhancing Circular Economy Through Sustainable Finance Practices in the Western Balkans

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Abstract. The Western Balkan Six (Albania, Bosnia and Herzegovina, Kosovo, Montenegro, North Macedonia and Serbia) are progressively aligning with the EU Green Deal and the Green Agenda for the Western Balkans; yet the extent to which emerging sustainable finance flows support a circular built environment remains unclear. This paper presents a desk-based mapping of sustainable finance initiatives in the region since 2015, focusing on instruments and frameworks with potential relevance for buildings and construction. Using mainly secondary sources—policy documents, sovereign and bank frameworks, project descriptions, impact reports and grey literature—the study compiles a database of (i) sovereign and corporate green and sustainability bonds, (ii) green credit lines and blended-finance programs led by international financial institutions and the EU, (iii) regional and national sustainable finance frameworks (including the WB6 Green Bond Standard and emerging taxonomy work), and (iv) green retail and corporate banking products such as energy-efficient housing loans and SME "Go Green" credit lines. The review shows that sustainable finance in the Western Balkans is expanding but remains concentrated in a limited set of sovereign and bank bond issuances and a small number of large regional credit facilities. At the same time, new regional standards and taxonomies, together with growing green lending portfolios, create an enabling environment to direct more capital towards circular building projects. The paper concludes by identifying key knowledge gaps and suggesting next research steps to better understand how existing sustainable finance instruments can more effectively support circular construction in the Western Balkans.

Keywords: Sustainable finance · Western Balkans · Circular economy · Built environment

1 Introduction

The built environment plays a central role in sustainability transitions due to its high resource use, energy consumption, and greenhouse gas emissions, making it a key target for climate mitigation and circular economy strategies. Financial instruments such as green bonds and green credit lines are increasingly used to channel capital toward

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sustainable investments, while access to finance for circular projects depends on supportive regulatory frameworks, financial-sector development, and credible sustainability standards. This paper aims to map and analyze sustainable finance initiatives in the Western Balkans with potential relevance for the circular built environment, providing an overview of the evolving sustainable finance landscape and assessing its potential contribution to circular construction.

The paper is organized as follows. In the next section, a systematic literature review is offered. Later, the context and methodology of the study is presented, highlighting the WB agenda and its goals. The reminder of the paper will present the results of the conducted desk analysis. A special focus will be given to mapping financing instruments that support the circular economy prospect. Finally, the study will translate findings into policy recommendations for central/local government.

2 Literature Review

Financing gaps in sustainability transitions have increased attention toward mechanisms that mobilize private investment (Qadir et al., 2021). The built environment is widely recognized as a critical sector for achieving sustainability and climate goals due to its high consumption of energy and materials, as well as its substantial contribution to waste generation and greenhouse gas emissions (Adams et al., 2017). Circularity in the built environment involves material reuse, recycling, and lifecycle extension strategies (Adrian-Cosmin et al., 2023). However, the literature also highlights conceptual overlaps and ambiguities between circular economy principles and broader sustainability goals, suggesting that operationalizing circularity requires systemic changes in governance, regulation, and economic incentives (Kirchherr et al., 2017).

An important body of research examines the role of stakeholders in implementing circular economy practices in the built environment. Owojori and Okoro (2022) argue that while governments often lead circular economy policy development, the private sector plays a critical role in implementing circular solutions through investment, innovation, and value-chain collaboration. Evertsen and Knotten (2024) argue that circular transitions depend on networks of interdependent actors, including municipalities, developers, contractors, technology firms, and financial institutions. However, several barriers limit private-sector participation, including financial risks, lack of regulatory clarity, and technological constraints. These barriers highlight the importance of financial mechanisms and enabling policy frameworks that can support investment in circular construction projects.

Technological and informational infrastructures also play a key role in facilitating circularity. Yu et al. (2022) review ICT-based decision-support tools that enable circular resource management in construction and demolition activities. Technologies such as Building Information Modelling (BIM), Internet of Things (IoT), blockchain, and big data analytics can improve material traceability, support lifecycle assessments, and facilitate the recovery and reuse of building materials. Such digital tools are increasingly seen as necessary for enabling circular construction practices and improving transparency in material and financial flows. However, their adoption requires substantial innovation investment, which in turn calls for financial support (Thirumal et al., 2024).

From a financing perspective, Agyapong and Tweneboah (2023) highlight that circular economy investments depend on both firm-level readiness and broader financial environments. Their study demonstrates that access to circular finance is influenced by institutional factors such as financial-sector development, regulatory frameworks, and supportive policy environments. Griffiths et al. (2025) show that higher insurance costs for reused materials, fragmented supply chains, insufficient markets for secondary materials, and limited awareness of circular procurement practices all constrain adoption.

Overall, the literature suggests that while circular economy principles are increasingly applied to the built environment, implementation remains constrained by financial, technological, and institutional barriers. In particular, the relationship between sustainable finance mechanisms and circular construction remains relatively underexplored. This gap is particularly relevant in regions such as the Western Balkans, where sustainable finance frameworks are still evolving and where understanding how financial flows align with circular construction objectives remains limited.

3 Data and Analysis

3.1 Context: WB Landscape

The Western Balkans—comprising Albania, Bosnia and Herzegovina, Kosovo, Montenegro, North Macedonia, and Serbia—share a legacy of socialist economic systems followed by complex political and economic transitions in the 1990s. Many countries entered the post-socialist period with aging infrastructure, energy-intensive industries, and weak environmental regulatory frameworks (Pieterse, 1997; Kume & Llaci, 2000). Since the 2000s, EU integration has become a key driver of institutional reforms, influencing environmental regulation, energy policy, and infrastructure development (European Commission, 2023).

The adoption of the Green Agenda for the Western Balkans in 2020 marked a significant step toward aligning regional policies with the European Green Deal, emphasizing decarbonization, circular economy development, pollution reduction, and sustainable infrastructure investment (Regional Cooperation Council, 2021). International financial institutions such as the EBRD, EIB, and the EU have introduced green bonds, energy-efficiency credit lines, and blended-finance facilities to support investments in renewable energy and sustainable infrastructure (EBRD, 2023), though sustainable finance markets remain relatively small and fragmented compared to EU member states.

3.2 Desk Research Background

This study applies a desk-based exploratory research approach to map sustainable finance initiatives in the Western Balkans with potential relevance for the circular built environment. The analysis relies on secondary data sources published between 2015 and 2024 and covers all six Western Balkan economies. Data were collected from policy and regulatory documents (national climate and energy strategies, EU progress reports, and the Green Agenda for the Western Balkans), financial frameworks and disclosures (sovereign and corporate green bond frameworks, bank sustainability reports), project

documentation from international financial institutions (EBRD, EIB, World Bank, EU-funded programs), and institutional and grey literature from regional organizations and development agencies.

Based on this review, sustainable finance instruments and initiatives were categorized across seven themes: Strategy & Governance; Regulation, Disclosure & Data; Risk Landscape; Financial Sector Practice; Public Finance & Disaster Risk Financing; International Alignment; and Market Development & Awareness.

3.3 Findings: Mapping Sustainable Finance Initiatives in the Western Balkans

Strategy, Governance and International Alignment. Governments and financial authorities across the Western Balkans are gradually integrating climate considerations into national development strategies and financial-sector policies. The Green Agenda for the Western Balkans reinforces alignment with the EU Green Deal through the EU Economic and Investment Plan, EU4Green, and the Western Balkans Investment Framework (WBIF). The EBRD, EIB, and World Bank play key roles in supporting regulatory reforms, climate-risk integration, and green investment programs. Several countries have also begun exploring national sustainable finance taxonomies aligned with the EU taxonomy, though most initiatives remain at an early stage.

Table 1. Comparative Overview of Sustainable Finance Development in the Western Balkans

Country	Policies	Instruments	Programs	Built Environment Focus
Albania	NECP; Green Agenda	Green loans; EE finance	EBRD, WBIF, EU	Solar, building retrofit
Bosnia & Herzegovina	Energy Community; ESG emerging	SME green loans; EE finance	EBRD, EIB, REEP	Renovation; district heating
Kosovo	Energy reforms; EU alignment	EE loans; SME green finance	EBRD, World Bank	Insulation; heating systems
Montenegro	Climate policy; EU reforms	RE finance; green loans	EBRD, EU, WBIF	Transport; efficient buildings
North Macedonia	Green growth; EU alignment	EE loans; green SME finance	EBRD, EU4Green, REEP	Buildings; urban infrastructure
Serbia	Sustainable finance strategy	Green bonds; EE finance	EBRD, EIB, WBIF	Large-scale renovation; RE

Source: The Authors

Table 1 illustrates that while sustainable finance initiatives are present across all Western Balkan economies, their scale and maturity vary considerably. Serbia and North Macedonia have made relatively greater progress, while other countries rely more heavily

on international financial institutions and EU-supported programs. Across the region, investments are concentrated in renewable energy (RE) and energy efficiency (EE), while instruments explicitly targeting circular construction remain limited—consistent with the literature showing that early-stage sustainable finance frameworks tend to prioritize decarbonization over material circularity (Kirchherr et al., 2017).

Regulation, Disclosure and Data. Regulatory frameworks for sustainable finance remain fragmented across the Western Balkans. Many countries are still in early stages of transposing EU sustainable finance directives, and the absence of standardized taxonomies and reporting systems continues to pose challenges for financial institutions and investors.

Table 2. Sustainable Finance Frameworks: Progress and Gaps in WB6

Country	Progress (Frameworks)	Gaps	Source
Albania	BoA Green Strategy; EIB support for taxonomy	Taxonomy and reporting still under development	EIB; BoA
Bosnia & Herzegovina	ESG roadmaps; EU-alignment efforts	Institutional fragmentation; no unified taxonomy or disclosure	World Bank
Kosovo	Central Bank roadmap (2025–2027)	No legal framework; taxonomy and ESG disclosure missing	World Bank
Montenegro	Climate-risk surveys; finance roadmap	Limited risk assessment; data and reporting gaps	CBCG
North Macedonia	Climate-risk plan; supervisory guidelines	Weak disclosure and reporting capacity	MIA; EIB
Serbia	Green bond; Sustainable Finance Framework	Taxonomy and risk frameworks still evolving	Ministry of Finance

Source: The Authors

Table 2 shows that all six economies have taken at least initial steps toward sustainable finance alignment with EU standards, but progress remains uneven and institutionally fragmented. In line with the ESG literature, these observations highlight that inconsistent reporting standards weaken the reliability of sustainability-related financial information and hinder market development (Eccles et al., 2014; Schoenmaker & Schramade, 2019). Serbia appears the most advanced due to its sovereign green bond and sustainable finance framework. Across the region, standardized taxonomies, climate-related disclosure systems, and comparable green-finance data remain incomplete, limiting transparency and

constraining the scale-up of sustainable finance—and, by extension, the ability to identify and support circular construction projects (Regional Cooperation Council, 2023; World Bank, 2023; OECD, 2020).

Risk Landscape and Financial Sector Practice. The region is exposed to physical climate risks including floods, wildfires, droughts, and earthquakes. Integration of climate risks into financial supervision is gradually gaining momentum through climate scenario analysis and stress testing, with technical support from the World Bank, EBRD, and EIB. However, limited climate-related data, the absence of national taxonomies, and a lack of standardized reporting frameworks remain significant challenges. This aligns with the literature emphasizing the importance of integrating lifecycle and material-related risks in the built environment (Ghisellini et al., 2016).

Financial institutions are gradually incorporating environmental considerations into lending practices. Programs such as the Green Economy Financing Facility (GEFF) and other regional energy-efficiency financing initiatives provide credit lines through local banks for investments in energy-efficient technologies and building renovation. The overall share of green loans in bank portfolios remains small, and financial institutions tend to prioritize lower-risk energy efficiency investments over more complex circular construction projects, in consistence with the literature (Agyapong & Tweneboah, 2023). This is consistent with findings in emerging markets, where ESG integration remains at an early stage (Rakočević et al., 2023). This suggests that the institutional capacity required to support circular finance—particularly in assessing lifecycle impacts and material flows—is still underdeveloped in the region.

Public Finance, Market Development and Awareness. Several Western Balkan governments have introduced elements of climate budgeting and are incorporating disaster-related risks into fiscal risk statements (World Bank, 2023; EU4Green, 2024). Disaster risk financing instruments remain relatively underdeveloped, with most disaster-related expenditures still financed through ad hoc budget reallocations or international assistance (World Bank, 2023; UNDRR, 2025; World Bank, 2024). The limited development of such instruments reduces the potential to support circular and resilient infrastructure projects (OECD, 2020).

Significant gaps in market awareness and capacity regarding sustainable finance persist. Many small and medium-sized enterprises still perceive sustainability requirements as regulatory burdens rather than economic opportunities (Pojani et al., 2025). Capacity-building efforts—through educational initiatives, professional training programs, and university courses on climate finance and environmental economics—are increasingly being introduced to strengthen the knowledge base of policymakers, financial institutions, and private-sector actors.

4 Conclusions

The findings suggest that while sustainable finance in the Western Balkans is expanding, its contribution to circular construction remains indirect and limited. Financial flows are primarily directed toward energy efficiency and renewable energy projects rather than circular material use or lifecycle-based construction practices. This reflects structural barriers including limited regulatory clarity, underdeveloped markets for secondary materials,

and insufficient risk-sharing mechanisms. The absence of standardized taxonomies and reporting frameworks constrains financial institutions from identifying and supporting circular investments. The strong reliance on international financial institutions indicates that domestic financial markets are still in an early stage of development.

Several policy recommendations emerge from the analysis. Governments should develop national sustainable finance taxonomies aligned with the EU framework, explicitly incorporating circular construction criteria. Financial institutions should expand existing energy-efficiency programs to include circular practices such as material reuse and design for disassembly. Public authorities should introduce targeted incentives—including subsidies and tax reductions—to stimulate demand for secondary construction materials. Capacity-building initiatives should be strengthened to increase awareness among SMEs and financial institutions. Finally, enhanced regional cooperation is needed to harmonize regulatory frameworks and facilitate cross-border investment in sustainable infrastructure.

This study relies on publicly available secondary data, which may not capture all ongoing sustainable finance initiatives; data availability varies across countries; and the exploratory design does not allow for causal inference. Future research could complement this analysis with primary data collection and case studies.

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Policy and Governance: Regulatory Frameworks, Certification Systems, and Leadership for Circularity

Barriers, Enablers, and Considerations Towards Circular Affordable Housing in Jordan: Insights Across Policy and Practice from Stakeholders' Interviews

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Abstract. Circular economy transitions in housing remain largely theorised in Global North contexts, with limited empirical evidence from affordable housing systems in the Global South. This study assesses the circular readiness of Jordan's affordable housing sector using 32 stakeholder interviews structured around 15 clusters of circular design practice contextualised for Global South. Findings are interpreted through a three-tier readiness framework reflecting the balance between barriers and enablers. Results indicate moderate but uneven readiness. Tier 1 clusters, such as water efficiency, basic energy measures, seismic robustness, and right-sizing, are routinely applied but largely compliance- and cost-driven. Tier 2 clusters, including waste-to-energy, locally sourced materials, indoor environmental quality measures, incremental housing, and demountable construction, remain pilot-based and constrained by regulatory rigidity, technical uncertainty, and weak market structures. Tier 3 clusters, such as adaptive reuse, material reuse pathways, stock–flow tools, green roofs, and cultural value preservation, remain aspirational due to systemic barriers. Across tiers, regulatory and policy constraints emerge as the dominant limiter of scaling. The findings provide transferable insights for advancing circular affordable housing in comparable Global South contexts.

Keywords: Circular Economy · Circular Design · Global South · Policy and Practice · Readiness · Sustainability Transition

1 Introduction

The construction sector is widely recognised as a critical frontier for Circular Economy (CE) transitions due to its resource use, waste generation, and long asset lifecycles [1]. In housing, circularity extends to socio-technical value retention across the building lifecycle [2]. Yet much of this scholarship is grounded in high-income contexts characterised by mature regulatory systems and established secondary-material markets, limiting its transferability to cost-constrained contexts [1]. Affordable housing in the Global South operates under affordability pressures, conventional construction logics, and limited

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institutional capacity [3]. Emerging research indicates that circular transitions in such contexts depend less on technological sophistication and more on regulatory reform and coordinated institutional action [4]. However, empirical assessments of sectoral readiness—how circular transitions are enabled or constrained in specific housing delivery systems—remain scarce.

Jordan represents a critical case. Sustained population growth and rapid urban concentration intensify housing demand under severe resource constraints [5, 6], particularly chronic water scarcity and high dependence on imported energy [7, 8]. Under these pressures, housing provision has prioritised cost minimisation and speed of delivery. Consequently, despite sustainability ambitions, affordable housing systems remain institutionally fragmented, with limited evidence of how sustainable design practices are systematically operationalised across governance and practice interfaces.

This study addresses this gap by evaluating the circular readiness of Jordan's affordable housing sector through analysis of barriers, enablers, and forward-looking considerations. Drawing on 32 stakeholder interviews based on a previously established database of 15 clusters of circular design practices contextualised for the Global South, the study develops a tiered readiness framework distinguishing embedded, selectively activated, and aspirational practices. The findings advance understanding of how circularity becomes structured or constrained within cost-sensitive housing systems and generate transferable insights for comparable Global South contexts.

2 Literature Review

This study builds on 15 clusters of circular design practices for affordable housing in Global South contexts, derived from a framework-informed review. Identified through cross-global case analysis, the clusters reflect affordability constraints, limited regulatory and industrial capacity, and strong socio-cultural embeddedness. Rather than abstract principles, they represent empirically tested construction and governance practices structured across seven sustainable development domains: material, energy, and water cycles; ecology; culture; wellbeing; and other value forms.

Within the technical domain, material-related practices dominate the literature. These span strategies aimed at avoiding new material demand (hereafter referred to as refuse), reduction, flexibility and reassembly, robustness, renewable resource use, reuse, repurposing, recycling, recovery, and documentation. "Refuse" avoids new material demand through converting existing structures into affordable housing [9]. Material reduction is achieved through right-sizing, lightweight and off-site construction, and life-cycle-based material selection [10]. Flexibility and reassembly rely on low-tech modular and prefabricated systems enabling incremental growth [11], while robustness practices prioritise seismic-responsive and durable structures [12]. Renewable material use emphasises locally sourced materials such as timber [13]. Reuse pathways close material loops such as plastic upcycling and selective deconstruction-based urban mining [14, 15]. Documentation practices, including material stock–flow models and decision-support tools, underpin informed decision-making [16]. Energy-related practices are centring on energy reduction, flexible energy use, and recovery. Energy demand is reduced through passive strategies combined with renewable systems [10]. Flexible energy strategies

emphasise energy shared systems [11], while recovery is addressed through waste-to-energy applications [14]. Similarly, water-related practices focus on reduction, flexibility, and recycling, primarily through decentralised systems such as on-plot retention, rainwater harvesting, rooftop storage, and greywater reuse [14]. Ecology-related practices reduce ecological pressure using green roofs, biodiversity-sensitive landscaping, and end-of-life strategies to limit landfill dependence [9]. Within the social domain, culture-related practices prioritise affordability, flexibility, and inclusion through shared and adaptable spaces, co-design processes, and job creation [11, 15]. Wellbeing-related practices address toxicity reduction and indoor environmental quality through non-toxic materials, improved ventilation and daylighting, and thermal and acoustic comfort measures [9]. Other value forms preserve cultural and functional value over time by maintaining local identity and aesthetic continuity [11]. Circular affordable housing in the Global South relies on context-sensitive, low-tech, socially embedded practices.

Additionally, this study adopts a seven-category analytical framework to assess circular readiness in Jordan's affordable housing sector, encompassing: regulatory and policy; institutional and organisational; financial and economic; technical and technological; knowledge and awareness; market and supply chain; and cultural and behavioural dimensions. These categories reflect widely recognised domains for evaluating CE adoption in construction [22, 23]. Within this framework, barriers, enablers, and future considerations are differentiated by their current level of operationalisation. Barriers denote existing constraints that hinder circular implementation, such as regulatory rigidity, governance fragmentation, financial limitations, technical gaps, weak markets, and socio-cultural resistance [17–19]. Enablers refer to existing capacities and initiatives that actively support implementation, including supportive policies, institutional coordination, technical expertise, and emerging market structures. Future considerations capture forward-looking reforms and interventions identified by stakeholders as necessary to strengthen readiness and scale circular practices, such as regulatory reform, expanded pilots, innovative financing, capacity-building, and market development [4].

3 Methodology

This study adopts a qualitative, exploratory design to examine barriers, enablers, and future considerations shaping circular design implementation in Jordan's affordable housing sector. It draws on 15 clusters of circular design practices identified in the literature (Sect. 2) synthesised across seven socio-technical impact areas [20]. These clusters informed the development of the semi-structured interview questions. Semi-structured interviews were used as they are well suited to examining implementation barriers and enabling conditions in complex housing systems [19], and were further informed by prior literature (Sect. 2).

Stakeholders were identified through institutional mapping of Jordan's housing and sustainability landscape, followed by purposive and snowball sampling to include actors across governance (ministries, municipalities, regulatory bodies) and practice domains (developers, NGOs, practitioners, academia) [21, 22]. Participants were selected based on professional role, experience, and a minimum of three years' engagement in housing or sustainable construction. In total, 32 stakeholders participated. Interviews were

conducted between December 2024 and April 2025 (45–90 min), in Arabic or English, and transcribed verbatim. Data were analysed using deductive thematic analysis aligned with the predefined circular design framework and associated barrier–enabler categories [23], supported by NVivo 14. Ethical approval was obtained from the Welsh School of Architecture Research Ethics Committee (Approval No. 24029), and all participants provided informed consent.

4 Results and Discussion

Of the respondents, 56% represented top-down actors from regulatory and municipal institutions, while 44% reflected bottom-up perspectives from practitioners, private developers, and academia, ensuring balanced governance and implementation insight. Participants were highly experienced: 50% reported 11–20 years, 19% more than 20 years, and 31% between 6–10 years of professional experience. Institutional representation included key ministries (Public Works and Housing; Environment), the Housing and Urban Development Corporation, Greater Amman Municipality, professional bodies (Jordanian Engineers Association; Jordanian Green Building Council; Royal Scientific Society), private developers, waste firms, and international organizations such as UN-Habitat, GIZ, and GGGI. Most respondents held senior or advisory roles involved in decision-making, technical guidance, or project implementation, providing informed perspectives on circular design barriers, enablers, and future pathways in Jordan's affordable housing sector.

To interpret the results, clusters of circular design practices were organised into tiers of activation based on relational patterns in the heatmap (Table 1), reflecting the balance between current barriers and enablers. Heatmap values indicate the frequency with which respondents identified each factor (0–9 negligible; 10–19 secondary; ≥20 primary). Darker cells may signal either entrenched constraints or strong enabling conditions and are therefore interpreted relationally across clusters. Three tiers of readiness were identified. Tier 1 (relatively activated) clusters exhibit at least two activated enabler categories (primary or secondary), including technical and regulatory and/or institutional support, demonstrate routine implementation, and face no more than two primary barrier categories. These reflect pragmatic circularity embedded through compliance, cost-efficiency, or technical maturity. Tier 2 (selectively activated) clusters show partial readiness, with one or two activated enablers but constrained by two to three primary barriers, limiting uptake to pilots or specific projects. Tier 3 (latent) clusters display minimal readiness, characterised by one or no activated enablers and dominance of three or more primary barriers, remaining largely aspirational and misaligned with prevailing regulatory and delivery logics. Read relationally, this tiered structure frames the findings as patterns of readiness, distinguishing embedded practices from those that are conditionally applied or not yet operationalised in Jordan's affordable housing sector.

Tier 1 includes four clusters representing the highest observable circular readiness level in Jordan's affordable housing sector, although readiness remains partial rather than fully circular. First, water-efficiency is the most consistently activated cluster, although mainly through fixture-led measures. Low-flow fixtures are widely used because they are affordable, available, easy to install, and culturally accepted. However, system-scale measures such as greywater reuse and rainwater harvesting remain

Table 1. Summary of Captured Barriers, Considerations, and Enablers

		Technical Domain												Social Domain		
Circular Design Clusters for Global South Contexts		Adaptive reuse	Incremental and expandable housing	Dry connections, demountable components	Seismic-responsive and durable structures	Right-sizing, lightweight systems	Material flow models, decision tools	Local materials	Material reuse pathways	Basic energy efficiency measures	Waste-to-energy applications	Water efficiency measures	Green roofs, planting	Shared spaces, job creations, user acceptance	Non-toxic materials, IEQ measures	Preservation of local identity
Barriers	R1	31	32	28	3	16	29	30	28	5	20	19	14	27	11	16
	I1	2	1	0	19	1	4	0	0	20	3	3	0	32	9	9
	F1	32	10	13	32	3	21	3	9	26	23	23	29	16	22	32
	T1	22	7	3	7	0	32	11	32	13	25	14	32	6	13	32
	K1	0	18	19	21	21	31	13	5	19	15	20	14	20	25	0
	M1	2	9	18	3	15	6	29	26	5	16	0	15	1	6	8
	C1	30	32	32	10	32	19	29	23	14	8	18	4	15	23	11
Considerations	R2	32	31	24	17	15	21	15	22	20	22	23	13	2	17	1
	I2	19	18	21	26	20	20	30	31	24	31	12	8	24	5	6
	F2	32	17	16	24	8	17	14	27	21	22	20	10	1	3	7
	T2	26	12	16	32	30	27	24	19	21	19	15	32	13	8	26
	K2	1	13	24	13	21	29	15	11	16	2	11	7	32	27	3
	M2	0	3	7	2	3	0	7	5	1	2	0	1	0	2	1
	C2	0	4	4	0	4	2	2	1	6	2	11	2	17	18	19
Enablers	R3	0	0	0	12	3	2	1	4	6	4	6	2	1	5	2
	I3	3	6	7	9	15	15	10	11	12	11	12	10	11	10	9
	F3	0	0	0	6	8	3	2	5	6	4	15	2	4	5	4
	T3	18	12	14	15	25	18	11	13	17	10	20	8	5	14	6
	K3	0	1	1	3	4	6	8	7	9	6	13	7	8	5	5
	M3	9	3	3	4	7	4	4	6	6	3	10	4	2	4	4
	C3	5	4	2	3	4	3	4	4	5	2	11	5	11	4	9

*Note: R = Regulatory and policy; I = Institutional and organisational; F = Financial and economic; T = Technical and technological; K = Knowledge and awareness; M = Market and supply chain; C = Cultural and behavioural. The suffixes indicate analytical category: 1 = Barriers, 2 = Future considerations, and 3 = Enablers. Values indicate the number of respondents, based on 32 interviews. The frequency levels are interpreted as follows: Negligible = 0–9 respondents, equivalent to 0–28%; Secondary = 10–19 respondents, equivalent to 31–59%; and Primary = ≥20 respondents, equivalent to ≥63%.

marginal despite pilots in Mafraq, Ajloun, and Ghor Safi, where regulatory ambiguity, approval delays, maintenance concerns, and fragmented institutional responsibility still restrict uptake. Circularity therefore advances where solutions are low-risk, low-cost, and simple to manage. Second, basic energy measures, including shading, solar water heaters, and rooftop PV, are technically familiar but largely compliance-driven. Financial pressures, lowest-cost procurement, institutional weakness, and limited monitoring reinforce minimum-standard implementation, described by one practitioner as "*a tick-the-box approach*." Progress requires performance-based codes, monitored pilots, and lifecycle-oriented evaluation. Third, seismic robustness is embedded through the Jordanian Seismic Code, ensuring baseline structural safety, yet affordability pressures, lowest-bid procurement, and knowledge gaps, including perceptions that "*heavier means stronger*", limit lightweight or performance-based alternatives. Similarly, right-sizing and material efficiency are applied pragmatically through compact layouts and simplified finishes, while cultural preference for reinforced concrete, limited familiarity, and weak market confidence constrain wider adoption of light-gauge steel or prefabricated panels.

Across Tier 1, readiness reflects pragmatic circularity shaped by compliance, affordability, technical maturity, and selective experimentation, rather than explicit circular design integration. Further progress depends on regulatory reform, monitored demonstrations, and professional capacity-building across policy and practice.

Tier 2 includes five clusters that reflect selective, project-dependent activation rather than embedded routine practice. First, waste-to-energy is technically proven beyond the housing sector, particularly through municipal landfill gas recovery at Al-Ghabawi and other industrial, agricultural, and wastewater-related applications. However, its connection to affordable housing remains weak because waste data, segregation systems, capital investment, licensing arrangements, and cross-sector coordination are still insufficiently developed. Progress therefore depends on coordinated pilots, clearer regulatory pathways, improved waste sorting, and targeted incentives that link energy recovery to housing delivery. Second, locally sourced materials are experimentally viable but not yet systemically embedded. University and research pilots, eco-lodge projects, NGO-led applications, and small private experiments demonstrate clay plasters, earth blocks, agricultural-waste composites, and other context-sensitive alternatives. Yet these materials remain outside mainstream affordable housing because certification, standards, procurement routes, supply-chain confidence, and cultural acceptance continue to favour conventional concrete-based construction. Scaling requires certified testing, code reform, pilot housing blocks, and production incentives. Third, non-toxic materials and IEQ measures show partial uptake through insulation, glazing, shading, ventilation, daylighting, and low-VOC finishes. However, implementation is still framed mainly around comfort and energy reduction rather than holistic health-oriented design, with affordability pressures, contractor knowledge gaps, weak enforcement, and limited awareness restricting deeper integration. Embedding IEQ standards and strengthening professional training are therefore central to advancement. Finally, two clusters reflecting the incremental,

modular, and dry demountable systems are technically compatible with Jordan's reinforced concrete frames and visible in family-driven extensions, NGO projects, camp-based or temporary structures, worker housing, and pilot applications. However, affordable housing integration remains limited by regulatory rigidity, absent standards for staged expansion and reversible connections, cultural preference for fixed construction, contractor unfamiliarity, and finance models favouring completed units.

Overall, Tier 2 circularity reflects conditional circularity: these practices are not absent, but they remain fragmented, risk-dependent, and weakly procurement-integrated. Their advancement requires regulatory alignment, certification pathways, housing demonstrations, market development, and targeted capacity-building.

Tier 3 includes six clusters that represent latent circular readiness, largely misaligned with prevailing regulatory, financial, and delivery logics. First, converting existing structures is visible mainly in small heritage restorations in downtown Amman and Salt, often NGO - or tourism-driven, but it is not yet a systematic affordable housing pathway. Second, material stock–flow tools, including LCA, material passports, and digital tracking, remain confined to academic, donor-funded, or internal organisational applications, with minimal integration into approval, procurement, or lifecycle decision-making. Third, material reuse pathways are tested through recycled aggregates, repurposed plastics, agricultural-waste composites, and factory recycling, yet weak certification, absent standards, fragmented supply chains, and low market trust continue to favour virgin materials. Fourth, green roofs and planting appear in institutional, high-end, or municipal greening projects, but remain difficult to mainstream in arid, cost-sensitive housing due to irrigation, maintenance, waterproofing, structural, and affordability concerns. Fifth, shared spaces, accessibility, and participatory practices appear in NGO, UN-supported, municipal, prototype, and informal self-build contexts, but remain poorly formalised. Finally, local identity preservation is visible through stone façades, courtyards, shaded spaces, and heritage-sensitive projects, yet cost-driven standardisation reinforces repetitive housing models.

Across Tier 3, circularity remains structurally constrained and aspirational, requiring regulatory reform, technical frameworks, demonstrations, and institutional capacity-building.

5 Conclusion: Where Are We Now and Where Are We Heading?

This study assessed the circular readiness of Jordan's affordable housing sector through stakeholder analysis of barriers, enablers, and future pathways. Findings show moderate but uneven readiness: practices are most embedded where they align with cost-efficiency, regulatory compliance, or technical familiarity, while others remain limited to baseline use, isolated pilots, or sector-specific experimentation. Regulatory constraints reinforce cost-driven delivery that prioritises short-term affordability over lifecycle value and adaptability, making circular housing primarily a governance and implementation challenge. Progress requires regulatory and procurement reform, circular approval and financing criteria, stronger certification and monitoring, and scaled demonstrations. While grounded in Jordan, the findings offer transferable insights for comparable Global South affordable housing systems.

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Integrating Circular Economy and the Water–Energy–Food Nexus for Resource Self-sufficiency in Cities: An SWOC Framework Approach

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Abstract. Cities are major consumers of water, energy, and food. However, these systems are often managed in isolation, leading to inefficiencies and resource losses. By adopting circular approaches that close resource loops and promote sectoral integration, cities can move toward greater resource self-sufficiency. This paper aims to explore the integration of the Circular Economy (CE) circular logic with Water–Energy–Food (WEF Nexus) systemic logic as complementary pathways to promote urban resource self-sufficiency. To this end, a SWOC-based assessment (Strengths, Weaknesses, Opportunities, Challenges) is used to identify enabling and constraining factors affecting the integration of the CE and WEF nexus at the city scale. For this, the core circularity principles by Ellen MacArthur are examined, considering the nexus principles of water, energy, food resources, and their interactions. The results show how the integration of CE principles, "Eliminating waste and pollution", "Circulating products and materials", and "Regenerating nature" in WEF systems can improve urban resilience, promote resource efficiency, system thinking, and support sustainable self-sufficiency. The findings create a structured understanding for future research and for developing urban circularity policies that can contribute to urban resource self-sufficiency and support the design of integrated circular strategies.

Keywords: Circular Economy · WEF Nexus · Self-Sufficiency · Circular Cities · SWOC Analysis

1 Introduction

Cities' rapid growth has led to significant environmental challenges. They consume 75% of the world's natural resources and 80% of global energy supplies and are responsible for over 50% of solid waste [1]. On one hand, the interconnected resources of water, energy, and food, known as the WEF Nexus, are closely linked to the abovementioned

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environmental challenges. To address these challenges, cities must shift to sustainable, integrated resource management strategies such as the circular economy (CE) and self-sufficiency approaches, which enable cities to meet increasing resource demands while ensuring current and future generations' well-being and ecological balance [2]. Despite this massive resource use, cities manage the fundamental resources of water, energy, and food separately, missing key opportunities to circulate resources across systems. For instance, water treatment demands 3–5% of urban energy, while wastewater carries valuable nutrients that could fertilize urban agriculture, and food waste generates methane emissions and missed biogas opportunities [3]. This silo approach prevents the capture of synergies, such as greywater reuse for cooling systems or solar thermal panels integrated with rainwater harvesting. On the other hand, CE offers a systemic alternative to the linear 'take-make-waste' model by keeping resources in use and regenerating natural systems, with potential to address cities' resource consumption and siloed inefficiencies [4]. According to the Ellen MacArthur Foundation (EMF), CE rests on three core principles that could transform urban resource management:1) Eliminate waste and pollution: Products and materials are designed so that waste and pollution are avoided from the start, nothing is discarded, and every output becomes an input elsewhere. 2) Circulate products and materials: Resources remain in the economy at their highest value through reuse, repair, refurbishment, and recycling, creating closed loops across water, energy, and food systems rather than siloed management, and 3) Regenerate nature: Rather than extracting from ecosystems, CE actively restores natural systems through regenerative agriculture, reforestation, and soil health, reversing urban environmental degradation. Various studies have explored the implementation of CE in the built environment [5–7], but there is a lack of integrated approaches to consider fundamental resource management [6] and their intersection through a nexus approach.

This paper investigates how the core CE principles, proposed by the EMF, can integrate with the WEF nexus to enable urban self-sufficiency. This study addresses this issue through the SWOC (Strengths, Weaknesses, Opportunities, Challenges) analysis in urban contexts. SWOC is a variant of SWOT that replaces "Threats" with "Challenges". Instead of viewing external risks as uncontrollable dangers, SWOC considers them as obstacles that can be addressed through proactive solutions [9]. This perspective promotes a more positive and action-oriented approach, which helps address systemic issues in complex socio-technical systems such as cities, providing a more dynamic and comprehensive basis for strategic planning [10].

2 Methodology

This study uses a qualitative, conceptual research approach, using the SWOC framework to assess the integration of Circular economy principles and the WEF nexus at the city scale to support resource self-sufficiency. A qualitative literature analysis approach was applied, and a total of 13 peer-reviewed publications were systematically selected from databases such as Scopus and Google Scholar, using keywords including "circular economy", "WEF nexus", "city", and "self-sufficiency". Additional institutional reports from organizations such as the Ellen MacArthur Foundation and the Organisation for Economic Co-operation and Development were included to complement academic sources.

The inclusion criteria focused on English-language publications from 2020 onwards that address the interconnections between CE and WEF systems in urban contexts or discuss related circular strategies. Relevant information from the selected sources was extracted, coded, and synthesized. First-order qualitative codes were derived from the literature and grouped into thematic factors reflecting enabling and limiting conditions for CE-WEF integration (Fig. 1).

To structure the analysis, a SWOC framework was developed following three steps. First, enabling and limiting factors were identified through coding and literature synthesis. Second, these factors were linked to CE principles and WEF nexus dimensions to assess how they support or constrain urban resource self-sufficiency. Third, factors were classified based on (i) their origin (internal vs. external relative to municipal boundaries) and (ii) their impact (positive vs. negative influence on CE-WEF integration). Accordingly, Strengths and Weaknesses refer to internal municipal factors within municipal control, while Opportunities and Challenges refer to external system-level factors beyond municipal control and authority. The city boundary was defined as the municipal administrative boundary, consistent with standard EU urban studies [10].

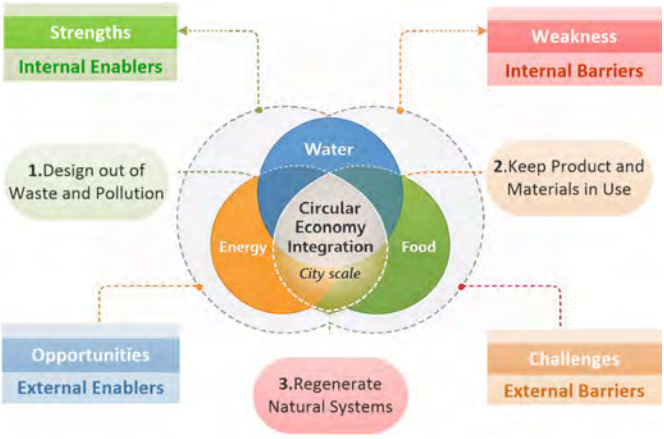


Fig. 1. Conceptual SWOC framework of CE-WEF integration, based on the EMA principles

Three authors independently conducted the classification process. Any discrepancies in categorization were resolved through consensus discussion to ensure analytical consistency and reduce subjective bias. The methodological novelty of this study lies in the structured integration of SWOC analysis with CE and WEF nexus frameworks at the urban scale.

3 SWOC Analysis

The SWOC analysis identifies 15 key factors influencing the integration of the CE and the WEF nexus in cities. These factors refer to technical solutions, governance structures, socio-economic conditions, and data and knowledge availability. In total, eight enabling

factors (4 Strengths and 4 Opportunities) and seven limiting factors (4 Weaknesses and 3 Challenges) were identified and categorized by their impact domain, whether internal (S and W) or external factors (O and C), see Table. 1.

Table. 1. Enabling and limiting Factor Mapping of CE-WEF integration in cities

Factor	Influence	Domain
Conceptual alignment [11–13]	Enabling	Internal
Synergies of Methodologies & existing tools [11–13]	Enabling	Internal
Resource recovery [13, 14]	Enabling	Internal
Environmental benefit [14, 15]	Enabling	Internal
Economic barriers [14, 16]	Limiting	Internal
Data and knowledge gaps [11, 12]	Limiting	Internal
Methodological silos [11, 17]	Limiting	Internal
Food dimension weak [11]	Limiting	Internal
Policy alignment and shared commitment [15, 18]	Enabling	External
Circular cities movement [16, 20]	Enabling	External
Collaboration across stakeholders [20], [21]	Enabling	Internal
Available Finance [16], [21]	Enabling	External
Stakeholders' resistance [22],[21]	Limiting	External
Few urban case studies and best practices [4], [21]	Limiting	External
Governance fragmentation [11], [21]	Limiting	External

Strengths (Internal Enablers). Among identified internal enablers, *Conceptual alignment* between CE and WEF was the most cited factor, which provides theoretical synergy among systems thinking, resource efficiency, and waste elimination, and a theoretical foundation for integration. This integration considers all CE principles across the WEF systems. Additionally, *Methodological synergies* build on existing tools, including LCA, material flow analysis (MFA), geographic information systems (GIS), input-output analysis in CE and WEF studies, and urban metabolism models [11], without necessitating entirely new frameworks. In addition, Resource *recovery* enables material circulation. Examples include energy recovery through biogas and nutrient recovery in food systems and wastewater treatment [14], which can directly reduce external dependence and improve resource self-sufficiency. Lastly, *Environmental benefits* are another enabling factor; accordingly, optimization models prove that implementing CE principles through integrated WEF planning could reduce GHG emissions by 20–40% and result in 15–25% resource savings [14] across WEF sectors, promoting waste elimination and material circulation.

Weaknesses (Internal Barriers). Among the internal barriers, *Economic barriers* include the high capital expenditure (CAPEX) required to build or upgrade recovery and

reuse infrastructure, such as advanced water treatment plants or energy recovery systems [14], which often exceed city budgets. Furthermore, funding is usually distributed separately across WEF sectors, making it difficult to combine financial resources for integrated projects. This siloed financial structure discourages cross-sector collaboration and limits the implementation of CE-WEF. *Methodological silos* are another major barrier to CE-WEF integration. Although many existing tools and frameworks can complement one another, they are usually developed independently by different sectors. As a result, these tools cannot readily share data or integrate their methods, making it difficult to produce integrated analyses or coordinated planning. This lack of interoperability limits the ability to identify and apply the full potential of CE-WEF synergies. *The data and knowledge gap* is also a barrier that strongly limits the integration of the CE and the WEF nexus at the urban level. Most cities lack detailed, high-resolution data on how water, energy, and nutrients flow [11]. Without this data, it becomes difficult to monitor and manage key flows such as water consumption, energy use, and nutrient recycling. Additionally, existing indicators are often sector-specific and not harmonized across sectors, which results in inconsistent monitoring and limited comparability. This also restricts the assessment of circular performance and the ability to track how effectively cities eliminate waste and circulate resources across sectors. Lastly, although little literature mentioned it, an important barrier is that the *food dimension* is often overlooked *in* CE-WEF integration studies in cities. More than 80% of existing studies focus primarily on the water and energy sectors, paying little attention to food-related aspects such as production, consumption, and waste management [11]. This imbalance limits a full understanding of how resources interact and reduces the potential for CE-WEF integration.

Opportunities (External Enablers). *Policy alignment* is among the most frequently cited enablers in the literature. Shared strategies such as the EU Green Deal, the SDGs, and national CE roadmaps provide a common framework that advances both climate and nature objectives. For instance, CE-WEF integration contributes to multiple SDGs simultaneously, particularly Goals 2, 6, 7, 11, 12, and 13 [15]. *The Circular Cities movement* provides platforms for integrating CE principles into urban master planning, which help cities coordinate actions across sectors, align policies, and design strategies that promote resource efficiency and circularity at the city scale. *Stakeholder collaboration* is another enabler that creates opportunities for joint solution development. By involving public authorities, private sectors, academia, and civil society, it promotes shared responsibility and integrated approaches to advancing CE-WEF implementation in cities. *Available financial mechanisms and funding programs* increasingly support CE-WEF nexus initiatives. There are CE and WEF funding at the EU and national levels that support cities in piloting integrated projects, technologies, and scaling up CE solutions across WEF sectors.

Challenges (External Barriers). *Stakeholder resistance* is a limiting factor that reflects low cross-sector awareness, even when common goals and shared interests exist. This limits collaboration among sectors and slows the CE-WEF integration initiatives in urban contexts. *Few urban case studies* are another barrier. Only a few urban case studies demonstrate partial integration, with less than 10% achieving full implementation [21]. This limited experience results in a lack of best practices to guide broader CE-WEF

adoption. *Governance fragmentation* is also a key barrier caused by separate national agencies with overlapping or unclear responsibilities, which limits coordination and effective CE policy implementation in WEF sectors. See Table. 2.

Table. 2. SWOC factors of the CE-WEF integration in cities

Strengths	Weakness
-CE-WEF Conceptual alignment -Synergies of methodologies and existing digital tools -Resources recovery potential -Environmental benefits (GHG reduction, resource savings)	-Economic barriers -Methodological silos -Data and knowledge gap -Food dimensions weak
Opportunity	Challenges
-Policy alignment and shared commitment -Circular cities movement -Shared stakeholders -Available finance & funding	-Stakeholders' resistance to change and lack of cross-sector awareness -Few urban case studies and best practices -Governance fragmentation

Collectively, the SWOC analysis shows that several enabling and limiting factors influence the CE-WEF integration in cities. The results indicate strong conceptual and methodological support for integration, particularly through existing tools, resource recovery practices, and environmental benefits across WEF sectors. At the same time, the analysis highlights structural gaps, especially related to economic barriers, data availability, and the limited consideration of the food and agricultural dimension. Some factors may seem contradictory; for example, funding is available, but high internal costs still limit what cities can do; similarly, useful methods exist, yet they are often used separately, creating gaps across sectors. This contrast shows that having conceptual strengths or available resources does not automatically remove practical barriers.

3.1 Interdependencies Among SWOC Factors

Several SWOC factors are linked and reinforce each other. For example, weak governance makes it harder to collect shared data, which in turn deepens methodological silos. Similarly, high costs and the lack of real urban examples go hand in hand; when funding is tight, fewer pilots are tested, and without proven examples, it is harder to attract investment. On the positive side, strong policy alignment can help open up funding and bring stakeholders on board at the same time. This shows that tackling one factor at a time, without seeing the bigger picture, is unlikely to drive real change.

4 Conclusion

This study applied a SWOC framework to examine the factors influencing CE-WEF integration in cities to support urban resource self-sufficiency. The results show a strong conceptual link between CE principles and nexus-based resource management, particularly through strategies that promote resource circulation and waste reduction. However, moving from theory to practical implementation is still limited by fragmented governance, sector-based funding structures, and the lack of real urban examples. Improving coordination between sectors, integrated planning, and knowledge sharing can help cities better use circular resource flows. In this way, CE-WEF integration can support greater local resource recovery and reduce cities' dependence on external resources, contributing to more resilient and self-sufficient urban systems. However, future research should apply this framework to real urban case studies to validate its practical relevance. The authors are currently developing an empirical application of this framework in Guimarães, Portugal, which will be presented in subsequent work. Exploring the interdependencies among SWOC factors through systems mapping could also further strengthen the analytical depth of the framework.

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Green Fiscal Tools and Urban Circularity: Assessing Municipal Tax Incentives for Sustainable Building in Portugal

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Abstract. This paper examines how municipal green fiscal instruments can support sustainable and circular transitions in the Portuguese built environment. It clarifies the relationship between sustainability, green fiscal policy and circular economy by treating local fiscal incentives as enabling instruments for rehabilitation, energy performance, renewable energy and waste prevention. A comparative mixed-methods design is applied to eight municipalities selected to reflect differences in size, urban role, economic structure and fiscal-administrative capacity. Official regulations, budgets, tariffs and municipal strategies were coded across five instrument categories: IMI reductions, IMT reductions, construction-fee exemptions, renewable-energy incentives and pay-as-you-throw (PAYT) waste tariffs. The coding distinguishes presence, territorial coverage, implementation specificity and circular-economy relevance, allowing a comparative assessment of policy coherence and expected behavioural mechanisms. Results show strong heterogeneity: Lisbon and Porto present the broadest portfolios, while smaller municipalities rely mainly on isolated property-tax incentives. The analysis distinguishes between partial, pilot, and city-wide PAYT implementation and considers territorial coverage when classifying municipalities. Guimarães is identified as a municipality where PAYT mechanisms have been implemented within specific operational contexts. The paper proposes a transparent comparative approach for assessing local green fiscal instruments and identifies priorities for stronger uptake monitoring and policy evaluation.

Keywords: Municipal fiscal policy · circular economy · green tax incentives · sustainable built environment · local governance

1 Introduction

Urban areas concentrate population, economic activity and environmental pressures, making cities critical arenas for sustainability transitions. The built environment accounts for a large share of energy consumption, material use and waste generation in Europe

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[1]. Because buildings and infrastructure have long life cycles, municipal decisions on land use, licensing, rehabilitation and services can create long-term environmental consequences.

This article uses sustainability as the broad objective of reducing environmental pressures while maintaining social and economic value; green fiscal policy as the set of tax, fee and tariff instruments that changes economic incentives in favour of environmentally preferable choices; and circular economy as the more specific objective of reducing virgin material use, extending asset life, recovering resources and preventing waste [2–7]. Green fiscal policy is not circular by definition, but it may become a circular-economy instrument when it rewards rehabilitation instead of demolition, improves building performance, stimulates renewable energy, or links waste charges to generation and separation behaviour.

In Portugal, municipalities have fiscal autonomy over instruments such as the Municipal Property Tax (IMI), the Municipal Tax on Onerous Property Transfers (IMT), construction and urbanisation fees, and municipal waste tariffs. This paper assesses how selected Portuguese municipalities design and combine these tools, how coherent they are with circular-economy objectives, and what behavioural mechanisms they can plausibly generate.

2 Literature Review

The circular economy is a sustainability paradigm aimed at decoupling economic activity from resource consumption through closed material loops, product-life extension and waste minimisation [2–4]. In the built environment, circularity is especially relevant because buildings concentrate long-lived materials, energy demand and construction and demolition waste. Circular construction therefore requires technological innovation as well as institutional and economic incentives [5–7].

Environmental fiscal policy is grounded in the idea that taxes, charges and incentives can internalise externalities and shift behaviour [8–10]. Most empirical work addresses national tax instruments, but local governments may be well placed to implement place-based environmental policy because of their proximity to households, firms and urban assets [11–14]. Nevertheless, decentralisation improves environmental outcomes only when fiscal autonomy is accompanied by administrative capacity, policy coordination and monitoring systems [15, 16]. In Portugal, studies on municipal finance show significant differences in fiscal capacity and local policy choices [17, 18], but the specific role of green fiscal tools in supporting circularity in the built environment remains underexplored.

This study contributes by connecting three strands of literature: circular economy in the built environment, environmental fiscal policy and local governance. It treats municipal fiscal instruments as potential circularity tools when they are explicitly linked to life-cycle extension, energy and material efficiency, renewable energy, waste prevention or differentiated waste charging. The study contributes by providing a structured comparative approach for analysing the circular-economy relevance of municipal fiscal instruments. This distinction is relevant because not every environmental tax

incentive produces circularity effects; circular relevance depends on whether the instrument affects resource use, building-life extension, material recovery, waste prevention or differentiated user behaviour.

3 Methodology

3.1 Case Selection and Data Sources

A comparative mixed-methods design was adopted. The eight municipalities—Lisbon, Porto, Braga, Matosinhos, Guimarães, Vila Nova de Famalicão, Penafiel and Lousada—were selected to combine maximum variation and regional relevance. The sample includes the two largest urban centres, medium-sized industrial and service municipalities, and smaller municipalities with different fiscal and administrative capacities.

Data were collected from official municipal regulations, annual budgets, urban-planning by-laws, waste-tariff documents, sustainability strategies and official municipal websites. Only formally approved instruments were coded. Where public information did not confirm territorial coverage, uptake or fiscal magnitude, the instrument was recorded as limited or unverified rather than treated as fully implemented.

3.2 Coding Procedure and Operational Definitions

Five instrument categories were coded: IMI reductions, IMT reductions, construction and urbanisation fee exemptions or reductions, renewable-energy incentives, and PAYT waste tariffs. An instrument was coded as implemented when a formal regulation or municipal programme established an operative incentive. It was coded as partial when implementation was restricted to a pilot area, a specific parish, a limited user group, or a single waste stream.

Policy coherence was operationalised through four criteria: instrument diversification; circular-economy relevance, meaning support for asset-life extension, renewable energy, waste prevention or material recovery; integration with municipal planning or sustainability strategies; and implementation specificity, meaning clear eligibility rules, target users, territorial coverage and administrative procedures. These criteria assess policy design, not causal impact.

PAYT was defined as a waste-tariff model in which the variable component paid by users is linked to the quantity, volume, weight or authorised bags of residual waste generated, sometimes combined with incentives for recycling or bio-waste separation [19]. Partial PAYT implementation counts as 0.5 in the diversification score and is explicitly identified, avoiding overstatement of pilot or geographically limited systems.

4 Results

Table 1 presents the coding results for municipal green fiscal instruments. Particular attention is given to PAYT systems because their classification depends on territorial coverage, implementation scope and the specific waste streams considered. Matosinhos

is not treated as having a confirmed city-wide PAYT system, while Guimarães is classified as a municipality where PAYT mechanisms have been implemented, although its territorial scope and waste streams are qualified. This distinction is important because PAYT is a behavioural instrument only when the tariff signal is effectively linked to waste generation or separation behaviour.

Table 1. Municipal green fiscal instruments by category

Municipality	IMI	IMT	Fees	Renewables	PAYT	Score
Lisbon	Yes	Yes	Yes	Yes	Yes	5
Porto	Yes	Yes	Yes	Yes	Yes	5
Braga	Yes	No	Yes	No	Yes	3
Matosinhos	Yes	No	Yes	Yes	Partial/unclear	3.5
Guimarães	Yes	No	No	Yes	Yes	3
V.N. Famalicão	Yes	Yes	Yes	Yes	No	4
Penafiel	Yes	No	No	No	No	1
Lousada	Yes	No	No	No	No	1

Notes: "Fees" refers to construction and urbanisation fees. Partial PAYT is scored as 0.5. Matosinhos is coded cautiously because public information does not confirm city-wide PAYT. Guimarães is coded as PAYT because municipal sources identify implementation in the historic centre and related areas, with tariff reforms linked to bio-waste separation and recycling incentives [20–22].

Table 2. Comparative synthesis of policy coherence and implementation intensity

Municipality	Diversification	Implementation intensity	Circularity orientation	Governance integration
Lisbon	High	High	High	High
Porto	High	High	High	High
Braga	Medium	Medium	Medium	Medium
Matosinhos	Medium	Partial/unclear	Medium	Medium
Guimarães	Medium	Targeted/partial	Medium	Medium
Vila Nova de Famalicão	High	Medium	Medium	Medium
Penafiel	Low	Low	Low	Low
Lousada	Low	Low	Low	Low

Table 2 synthesises the qualitative coding of policy coherence. Diversification reflects the number of fiscal categories adopted; implementation intensity reflects territorial

scope and operational maturity; circularity orientation reflects the extent to which instruments are linked to rehabilitation, energy performance, renewable energy, waste prevention or material recovery; and governance integration reflects whether fiscal measures are connected to broader municipal planning, sustainability or waste-management strategies. The classification is comparative and design-based and therefore should not be interpreted as evidence of measured behavioural impact.

The results show substantial heterogeneity. Lisbon and Porto present the most diversified portfolios of green fiscal instruments, with measures distributed across taxation, construction regulation, renewable energy and waste management. Vila Nova de Famalicão and Matosinhos show intermediate diversification, although the classification of PAYT in Matosinhos reflects its reported implementation scope. Braga and Guimarães present narrower but relevant portfolios, while Penafiel and Lousada rely mainly on IMI-related incentives (Fig. 1).

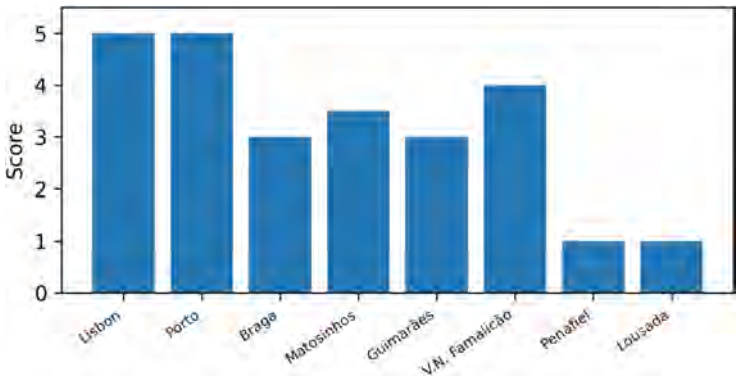


Fig. 1. Diversification score for green fiscal instruments by municipality. Partial PAYT implementation is scored as 0.5

To strengthen the empirical interpretation, the analysis distinguishes implementation intensity, fiscal magnitude, policy uptake and behavioural mechanism. Implementation intensity is coded as full, partial or unverified territorial coverage. Fiscal magnitude refers to the existence and scale of tax or fee reductions when publicly reported. Policy uptake refers to applications, users or operational areas when published. Behavioural mechanism identifies the expected channel—rehabilitation, energy investment, renewable energy, waste reduction or recycling. Because comparable uptake and revenue data are not available for all municipalities, the analysis remains descriptive and does not claim causal impact.

5 Discussion

The findings confirm that municipal fiscal autonomy is a relevant but unevenly exploited lever for promoting circularity in the built environment. The most diversified municipalities combine instruments that affect property costs, rehabilitation decisions, construction

fees, renewable-energy investment and waste behaviour. However, diversification alone does not prove effectiveness. The behavioural effects discussed here should be read as expected mechanisms derived from policy design, not as measured outcomes.

The analysis of PAYT systems illustrates why implementation intensity matters. A tariff model limited to a historic centre or selected service area cannot be interpreted in the same way as a city-wide system. Similarly, a municipality may formally promote recycling or bio-waste separation without operating a strict PAYT model based on residual waste quantity. For circular-economy analysis, the price signal, user coverage and waste stream determine whether the instrument can reduce residual waste, increase source separation or support material recovery.

The results also show an imbalance between green and circular fiscal strategies. Most instruments focus on energy efficiency and rehabilitation, while material circularity, construction and demolition waste, reuse of building components and life-cycle monitoring remain less visible. To become circular-economy instruments, green fiscal tools should be explicitly linked to circular objectives and accompanied by uptake data, monitoring indicators and coordination between finance, planning, environment and waste-management departments.

This study has limitations. The analysis relies on officially published institutional data and does not measure actual behavioural change, fiscal uptake, investment decisions or waste-reduction outcomes. Some municipal instruments also vary in territorial scope, operational maturity and public reporting quality, which limits direct comparability. For this reason, the results should be interpreted as an assessment of policy design and implementation conditions rather than as an evaluation of causal environmental impacts.

6 Conclusions

This paper provides a comparative assessment of municipal green fiscal instruments in Portugal and clarifies how such instruments can support sustainability and circularity in the built environment. The analysis demonstrates that municipalities possess relevant fiscal tools, but their deployment remains uneven and only partially aligned with circular-economy objectives. Larger municipalities tend to present more diversified portfolios, while smaller municipalities rely mainly on isolated property-tax incentives.

The main methodological contribution is an operational comparative approach that distinguishes instrument presence from policy coherence, implementation intensity and expected behavioural mechanisms. This comparative approach addresses the risk of overinterpreting descriptive counts as evidence of impact. The analysis of PAYT systems further shows that partial implementation must be coded separately and that waste streams, territorial coverage and tariff logic should be explicitly reported.

From a policy perspective, four priorities emerge: harmonising minimum definitions for green and circular fiscal incentives; expanding fiscal tools beyond energy efficiency to include material circularity and construction and demolition waste prevention; publishing uptake, fiscal cost and user-coverage data; and integrating fiscal policy with urban planning, rehabilitation strategies and waste-management systems. Future research should incorporate longitudinal data on applications, investments, fiscal revenues and waste flows to test the behavioural impacts suggested by this design-based assessment.

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Developing a Sustainable Built Environment: PISAC as a Governance and Collaboration Framework in Brazil

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Abstract. This paper presents PISAC - Parque de Inovação e Sustentabilidade do Ambiente Construído (Built Environment Innovation and Sustainability Park), a pioneering initiative designed to advance innovation and sustainability within the built environment sector. Effective innovative governance models capable of integrating research, industry, and public policies are essential to driving the global transition toward a sustainable and circular construction sector. In this context, PISAC is presented as a successful experience that strengthens communication, fosters partnerships, and supports research and development initiatives to enhance sustainability, innovation, and resilience across the entire life cycle of buildings and urban spaces. Established through a partnership among the University of Brasília (UnB), the Brazilian Chamber of Construction Industry (CBIC), and international institutions, such as the Building Research Establishment (BRE), PISAC is dedicated to the development, testing, and dissemination of innovative solutions for sustainability and resilience in construction. The article outlines the PISAC model as a comprehensive Governance and Collaboration Framework, demonstrating how its regulatory and operational mechanisms organize diverse stakeholders and resources within a collaborative and innovative ecosystem. Operating through four strategic pillars: Prototyping, Research, Training, and Products/Services, PISAC promotes systemic changes by creating a formal platform for shared action. As such, PISAC became an important enabler for the region's digital and sustainable transition. This paper, therefore, offers a valuable, replicable model for researchers, practitioners, and policymakers seeking to accelerate collaborative innovation toward a sustainable built environment.

Keywords: Governance · Collaboration Models · Innovation Platform · Sustainable Built Environment · Partnership

1 Introduction and Contextualization

The increasing global recognition of the built environment's profound impact on climate change and resource depletion underscores the imperative for innovative and sustainable practices. In this context, initiatives like the Parque de Inovação e Sustentabilidade do

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Ambiente Construído (PISAC) emerge as crucial platforms for driving systemic change by integrating diverse stakeholders and fostering a shared vision for a regenerative and resource-efficient future [1].

The Brazilian construction industry, while a significant pillar of the national economy, faces chronic challenges regarding productivity, waste management, and the slow adoption of digital technologies. Historically, the sector has been characterized by fragmented processes and a significant disconnect between laboratory-scale academic research and market-ready industrial applications.

PISAC operates through specialized ventures [2], the transition toward Circular Economy and Sustainable Construction in Brazil requires more than isolated technological interventions. It also demands a structured environment where innovation can be tested, validated, and implemented under real-world conditions.

The complexity of the Construction Industry's Production Chain (Cadeia Produtiva da Indústria da Construção - CPIC) demands a governance model that integrates the "Triple Helix" (Academia, Industry and Government) to overcome regulatory barriers and stimulate the adoption of high-performance materials and processes, such as Building Information Modeling (BIM) and industrialized construction techniques. PISAC addresses the lack of specialized infrastructure for large-scale prototyping and performance monitoring in tropical climates, which is a critical gap for the development of resilient urban solutions in the Global South.

Conceived through a strategic alliance between the University of Brasília (UnB), the Building Research Establishment (BRE), and the Brazilian Chamber of Construction Industry (CBIC), PISAC was formally established in 2011 to bridge the gap between academic research, industrial demand, and public policy. Its mission is to become a transformative hub for the built environment, driven by the development, rigorous testing, and broad dissemination of technological innovations concerning both processes and products. This vision aims for continuous innovation to transform the built environment, emphasizing sustainability and resilience throughout the planning, construction, and operational phases [1].

The genesis of PISAC traces back to foundational concepts developed in 1984 by Blumenschein (2004), subsequently nurtured through extensive research and pilot projects, such as the creation of the Laboratório do Ambiente Construído, Inclusão e Sustentabilidade (LACIS) in 2005 [2]. This trajectory led to the rigorous testing of various acceleration vectors for innovation within the CBIC. This commitment culminated in a formal Letter of Intent in 2011, involving the Ministry of Science, Technology and Innovation (MCTI), CBIC, Building Research Establishment (BRE), UnB, and the Federal District Government (GDF). Subsequent international agreements in 2012 and funding from the Brazilian National Fund for Science and Technology (FINEP) in 2013 consolidated PISAC as a collaborative network that catalyzes technical capabilities domestically and internationally, leveraging R&D to drive innovation and sustainability across the entire lifecycle of the built environment.

1.1 Research Methodology

This study adopts a qualitative and exploratory research approach based on a case study of PISAC. The research aims to analyze how governance structures, collaborative networks,

and innovation ecosystems can support the transition toward a sustainable and circular built environment in Brazil.

The methodological approach combines documental analysis of institutional regulations, strategic reports, and technical publications related to PISAC, together with a literature review on circular economy, sustainable construction, governance models, and digital transition in the built environment. The study also includes an analysis of operational initiatives and organizational structures developed within the PISAC ecosystem.

The study adopts the Triple Helix framework as an analytical lens to evaluate the interaction among academia, industry, government, and international collaborative networks.

The research is descriptive-analytical in nature and seeks to identify how PISAC functions as a governance and collaboration framework capable of supporting innovation, technological validation, and sustainability-oriented transitions in the construction sector.

2 The Built Environment Innovation and Sustainability Park (PISAC)

The PISAC is structured as an Integrated Research Center, a collaborative body linked to the Faculty of Architecture and Urbanism (FAU), the Faculty of Technology (FT), and the Faculty of Science and Technology for Engeneering (FCTE) at the University of Brasília (UnB) [2]. This institutional arrangement ensures a multidisciplinary approach, bridging the gap between theoretical research and practical application.

The partnership with the Building Research Establishment (BRE) from the United Kingdom provided the conceptual and methodological basis for the park, particularly the "Innovation Park" model [3]. PISAC continues to function as a "living laboratory" in which innovation is fostered through transparency and shared risk. This approach facilitates the validation of sustainable building technologies under real-world conditions, effectively bridging the transition from laboratory research to industrial implementation [1].

2.1 Strategic Axes and Operational Ventures

The center's activities are structured around four strategic pillars: Prototyping, which provides a controlled environment for testing innovative systems at Technology Readiness Level 7 (TRL 7); Research, driven by a network of over 100 active researchers focusing on materials performance and digital transformation; Training and Capacity Building, which bridges technical gaps through specialized courses and academic research; and Products and Services, dedicated to certifying market-ready solutions and BIM implementation workflows.

PISAC operates through specialized ventures that integrate these axes, such as the Praça de Protótipos (Prototyping Square), the park's core experimental site for full-scale validation the LACIS laboratory, focused on innovation vectors in the construction chain; and the UnB-BIM hub, dedicated to digital modeling and project management. Other key ventures include the CeCis (Center of Excellence for Sustainable Integrated

Communities), the NUESP (Nucleus for Studies and Research in Special Buildings), the SETT (Space Environment Think Tank) for space-related technologies, and the NUACRE (Nucleus for Studies of the Resilient Built Environment), which focuses on climate adaptation and building resilience [2, 4, 6].

Collectively, these ventures can facilitate the empirical validation of high-performance materials and circular economy strategies, directly contributing to the global transition toward regenerative building practices.

2.2 Collaboration among Academia, Industry, and Government

PISAC's effectiveness is rooted in a multi-stakeholder governance model that operationalizes the "Triple Helix" concept. This collaborative framework acts as a neutral platform where conflicting interests are aligned toward sustainability goals [1]. The Industry provides real-world challenges; the Academia develops and tests scientific solutions; and the Government supports the initiative through funding (MCTI/FINEP) and regulatory frameworks.

This network consolidates the Triple Helix and also incorporates a fourth strand, an international civil society and environmental network, ensuring local innovations and aligned with global standards [1, 3]. By involving the CPIC, PISAC facilitates technology transfer and reduces risks for private companies, which rely on the technical validation provided by UnB researchers.

Furthermore, the participation of entities like the Federal District Government (GDF) and the MCTI ensures that the sustainable solutions validated in the park are effectively integrated into public procurement and urban planning regulations, positioning PISAC as a strategic asset for Brazil's digital and green transition [1].

3 Research and Development in Sustainable Construction Technologies and Solutions for Circularity

The transition from linear production models toward circularity in the construction sector requires not only technological innovation but also integrated governance structures capable of supporting experimentation, validation, and collaboration among stakeholders. In this context, PISAC operates as a living laboratory that connects research, industry demands, and public policies to foster sustainable and regenerative practices within the built environment.

The following sections discuss the conceptual foundations of circular economy in construction and the role of digital technologies as enabling mechanisms for circularity and lifecycle management.

3.1 Conceptual Framework: Sustainable Technologies and Circular Economy

The construction industry is one of the most resource-intensive sectors, accounting for approximately 36% of global energy consumption and nearly 40% of energy-related carbon dioxide emissions. In response, the Circular Economy (CE) model has emerged as an alternative to the traditional linear economy. In the built environment, CE (Fig. 1)

is understood as a regenerative system that minimizes resource consumption, waste, and emissions by slowing, narrowing, and closing material and energy loops [4].

The literature identifies three main circularity strategies: narrowing (resource efficiency), slowing (extending the lifespan of buildings and components), and closing (recycling and material recovery) [5]. These strategies involve optimized design, durable construction, Design for Disassembly (DfD), and the reintegration of construction and demolition waste (CDW) into production chains.



Fig. 1. Circular Economy in the Built Environment - Source: www.RPSgroup.com

The implementation of CE in the built environment depends on environmental, economic, social, political, technological, and legal dimensions [6]. In this context, PISAC operates as a "living laboratory," testing sustainable technologies under real-world conditions while supporting the development of regulatory and collaborative frameworks for the Brazilian context. The digital transition also plays a central role in enabling circular practices.

Technologies such as Building Information Modeling (BIM) and Digital Twins support the creation of "Material Passports," which store information on the composition, performance, and maintenance history of building components [7]. These tools improve Life Cycle Assessments (LCA) and support material reuse across multiple lifecycles. Through initiatives such as UnB-BIM and the Praça de Protótipos, PISAC provides the infrastructure necessary to validate these digital workflows and circular strategies, reducing uncertainty and risks for the construction sector.

3.2 Impact and Contributions of PISAC for a Sustainable Built Environment

PISAC contributes to the practical implementation of circularity and sustainable technologies by reducing the risks associated with innovative solutions in the Brazilian construction sector. Through the Praça de Protótipos, the center provides a real-world testing environment that supports the transition from laboratory research to industrial-scale

applications (Technology Readiness Level 7 – TRL7). This validation process is particularly important for the adoption of high-performance materials in tropical climates, where long-term performance data are often limited [1].

One of PISAC's major contributions is the standardization of digital workflows for lifecycle management. Through ProBIM, the center developed the Manual para Projetos de Retrofit: Metodologia em BIM [8], which establishes standardized Scan-to-BIM procedures for the digitalization of existing buildings. The methodology includes laser scanning, point cloud processing, and the development of "As-Built" and "As-Is" models [8, 9]. These workflows support predictive maintenance, improve energy efficiency, and extend building service life, contributing to the "slowing loops" strategy of the circular economy.

PISAC also supports the "closing loops" strategy by evaluating construction materials through the Responsible Sourcing framework, developed in partnership with the Building Research Establishment (BRE). Data collected from monitored prototypes help support new technical standards and public policies related to sustainability and circularity [1].

In addition, PISAC contributes to professional training and capacity building. With more than 100 active researchers, the center promotes data-driven approaches for monitoring and predicting structural behavior, supporting resilient and evidence-based innovation in the built environment.

4 Challenges and Future Perspectives of PISAC

While the establishment of PISAC may represent a milestone for the Brazilian construction sector, its evolution involves navigating complex institutional challenges while simultaneously expanding its strategic horizons. The roadmap for the coming years focuses on consolidating its role as a primary driver for the digital and green transition.

A primary hurdle is ensuring long-term financial and operational autonomy through a self-sustaining model based on technical services, intellectual property management, and professional training within the interdisciplinary framework of FAU, FT, and FCTE [1, 2]. This institutional evolution is critical to supporting the mandatory transition to Building Information Modeling (BIM) in Brazil by 2028, in which PISAC serves as a strategic hub for methodology development and capacity building. By scaling Scan-to-BIM and maintenance workflows nationwide, the center helps both public and private sectors meet new regulatory requirements [10, 11].

Future perspectives also include advancing research on industrialized modular systems and climate adaptation strategies through the NUACRE and SETT ventures, using artificial intelligence and real-time monitoring to enhance urban resilience in the face of climate instability [1, 11]. Furthermore, PISAC's international partnerships must evolve from methodological exchange to joint global certifications, technology exchange, and shared innovation development [1, 5], reinforcing its role as an international reference for regenerative and resource-efficient built environments in the Global South.

5 Conclusion

PISAC stands as a comprehensive Governance and Collaboration Framework, uniquely positioned in the central part of Brazil to bridge the fragmented Brazilian construction ecosystem by institutionalizing structured interaction among academia, industry, and government. Grounded in its strategic pillars and reinforced by the physical infrastructure of the Praça de Protótipos, the center provides a unique environment for the empirical validation of innovative solutions, encompassing both processes and products of the construction industry. This integration strengthens the link between research and practice, ensuring that advancements are tested under real-world conditions before broader implementation.

The creation of standardized digital workflows, exemplified by the Manual para Projetos de Retrofit [11], further consolidates PISAC's role as a key enabler of national BIM mandates and as a cornerstone for sustainable asset management.

Beyond its national relevance, PISAC is evolving into an international hub for technological exchange, a transformation that will be critical to addressing global imperatives such as climate resilience and resource efficiency. While challenges related to financial autonomy and market absorption persist, the park's trajectory since its inception in 1984 demonstrates institutional maturity and offers a replicable blueprint for other regions across the Global South, where the demand for sustainable and inclusive construction practices is equally pressing.

The findings demonstrate that PISAC operates as an intermediary governance structure capable of integrating research, technological validation, and collaborative decision-making processes within the Brazilian construction sector. Its experience suggests that innovation ecosystems supported by institutional cooperation and digital integration can accelerate sustainable transitions in emerging economies.

Although challenges related to long-term financing and large-scale implementation remain, the PISAC model offers relevant insights for the development of collaborative frameworks focused on circularity, resilience, and sustainability in the built environment.

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Empowering Europe-Caucasus-Central Asia Cooperation Through Sustainable Bioeconomy Strategy

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Abstract. Bioeconomy is considered as a strategic opportunity in this paper to contribute connectivity between the Europe, Caucasus and Central Asia. Green economic model through combination of biotechnology and circular solutions is the main conceptual framework of the inter-regional connectivity. European bioeconomy regulations, strategies, as well as international initiatives like the Global Gateway and others are subject of analyses. Sustainability content is widely discussed for both Europe, Caucasus, Central Asia economic connectivity and biotechnology. Approximation of regulations, transfer of technologies, development of human resource capacities and building of common bioeconomy environment within the Europe-Caucasus-Central Asia landscape is prioritized in the study. Building of bioeconomy model as a cross-regional resilient infrastructure managed by nature-based and rule-driven solution is the main result of the paper. New standards, characteristics and criteria for bioeconomy market is designed for Europe-Caucasus-Central Asia cross-regional and transnational ecosystem as an interoperability concept.

Keywords: Bioeconomy market · bioeconomy strategy · Biotechnology · cross-regional

1 Introduction

Europe – Caucasus – Central Asia (hereafter: EuCauCA) connectivity takes a crucial role in terms of contemporary geopolitical tendences. Economic, environmental and social components are the main drivers of connectivity value chain that is developing rapidly. The research objective is to highlight connectivity institutionalization through bioeconomy cooperation between EuCauCA countries. This means to provide alternative connectivity solutions instead of physical ones. The objective is actual because there are obstacles in physical connectivity between EuCauCA countries and regulatory and academic frameworks like bioeconomy can be a real solution to promote connectivity institutionalization in the first stage of cooperation. In this context, the bio-content formulating bioeconomy is the main conceptual framework of cooperation. Obviously, European bio-content recorded significant achievements rather than Caucasus or Central

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Asian countries and the effective cooperation requires standards. Eco-design of economy to contribute sustainable processes is fundamental approach for these standards as a driver of EuCauCA bioeconomy market creation that is an objective of the study.

Investigation the role of standardization of science and regulation in bioeconomy, exploration the interaction between science and regulation as important drivers for bioeconomy standardization was discussed by Alexandra et al. [1]. The authors explained the importance of science and regulation within the bioeconomy concept focusing on standards that should be common in transnational landscape. This approach is applied in this paper within the EuCauCA cooperation over the economic, environmental and social aspects of bioeconomy. This means to manage a comprehensive framework of standards in sustainable bioeconomy strategies developed in EuCauCA landscape. The standards and strategies are considered in this paper are the main components of sustainable transition towards bioeconomy models, which can provide integration in European economic area through green economy. The New EU Circular Economy Resource Center established in 2024 can be an important hub for standards to provide synchronization, adaptation and implementation of processes in Caucasus and Central Asian countries to bring them in line with the European green economy. The paper discusses business ESG framework on sustainability index evaluation, social and ethical impact, strategical resilience, green infrastructure modernization and resource-management green approaches as the main strategic directions in cooperation between the EU Circular Economy Resource Center and EuCauCA. In this context, there are arguments that the bioeconomy and digital monitoring are important direction of circularity and green agenda that are discussed as part of the Circular Economy Resource Center's activity deriving from the Global Gateway implementation principles and priorities [2]. In order to provide digital monitoring in bioeconomy sector mentioned above, it is essential to provide digital connectivity between EuCauCA countries on sustainability issues that was discussed in many studies. In particular, Shirin and Silvia highlighted political and institutional arrangements for digital connectivity in the G20 countries, conceptualizing the link between digital connectivity and the SDGs [3].

Digital connectivity and sustainability discourse through the Global Gateway initiative across EuCauCA considering economic, environmental and social indicators should be discussed in the framework of digital inequality as well, because of different levels of digitalization and digital transformation exists between the Europe, Caucasus and Central Asia. In this context, according to Heeks, digital systems are significantly associated with inequality in the Global South and this association has traditionally been understood in terms of the digital divide or related terminologies whose core conceptualizations the exclusion of some groups from the benefits of digital systems [4]. Caucasus and Central Asian countries are associated with this inequality and the standardization on data, statistics and methodology are fundamental for overcoming inequality. This approach is in line with the European enlargement policy however one could argue that the slow accession process and uncertain membership perspectives (due to obstacles created by the incumbent EU members) were responsible for weakening enlargement-related incentives for the candidates to implement institutional reforms, which are often technically and politically difficult [5]. In case of EuCauCA cooperation within bioeconomy infrastructure is not discussed membership procedure, but integration in certain

fields like standardization, data management and monitoring methodology, as well as common policy approaches are the main directions.

In general, sustainable bioeconomy strategy based on standards, data, statistics, regulations and methodology are the main conceptual framework that considered reasonable in this study for EuCauCA cooperation modeling.

2 Literature Review

The studies on connectivity between Europe, Caucasus and Central Asia have a broad range of discourse, though the researches on bioeconomy conceptualization through cooperation of knowledge-rich and data-driven sustainability components is needed to examine and strengthen.

According to the Global Cooperation Barometer 2026, there are five pillars across global cooperation: trade and capital, innovation and technology, climate and natural capital, health and wellness, and peace and security, that are drawing on 41 indicators [6]. The most comparable pillars of the report within this study considered innovation and technology, and climate and natural capital. In case of innovation and technology the Compound Annual Growth Rate (CAGR) increased from 0.70% in 2012 to 1.65% in 2024, where cross-border data flows, IT service trade, IT goods/intermediate trade and individual using of internet were the main drivers. The climate and natural capital also increased sharply from 0.75% in 2012 to 1.10% in 2024 due to significant growth of indicators such as Global trade in low-carbon technology products, Finance: global climate mitigation, Finance: global climate adaptation. These indicators and international trend in this framework show increasing opportunity in EuCauCA cooperation. Albeit this opportunity, the concern is within fifth – peace and security pillar, where the indicators declined sharply from 1.05% in 2012 to 0.70% in 2024, as for conflicts escalated in many parts of the world. Considering these facts, the paper examines EuCauCA cooperation based on technology and sustainability components comparable for bioeconomy concept.

Obviously, most pillars and indicators of the Global Cooperation Barometer are subject of connectivity issues described in the Global Connectivity Report 2025, that investigates digital infrastructure strategy, universal and meaningful connectivity, the role of institutions and governance in this endeavor [7]. The report takes stock of the current state of connectivity worldwide and highlights persistent divides between and within countries. The same networks, – as mentioned in the introduction part of the report, that empower can also amplify inequality, carry misinformation and strain the natural environment. This is the main reason that standards and methods are discussed crucial in the context of EuCauCA large landscape cooperation.

Khachikyan and others examined EU bioeconomy in a wide spectrum based on the Global Gateway initiative, discussing the regulatory framework, main directions in production within circular economy concept, some statistical database, as well as bioeconomy compliance with the Global Gateway policy [2]. Taking into account that the Global Gateway touches largely technological and digital aspects within Eurasian landscape, this study focuses on the cooperation with Caucasus and Central Asian countries in this framework prioritizing bioeconomy-related tools.

The sustainable bioeconomy strategy requires examination of SDG principles. Parallel to this, digital connectivity in EuCauCA bioeconomy infrastructures is necessary as described, according to international reports [6], [7]. This means that arguments discussed by Shirin and Silvia on digital connectivity and SDGs is actual in bioeconomy cooperation within EuCauCA concept [3]. Furthermore, their analysis reveals that while holding a common matrix, have acquired different traits across the different countries of implementation. They zoom their analysis in on different types of interventions that involve technical interoperability between different entities including: public private partnership (PPP) initiatives to bridge the digital divide, public funding to expand connectivity beyond urban areas, and a range of last-mile interventions deployed to extend connectivity across areas where broadband coverage or service quality is systematically lower. In this study the last-mile intervention is a targeted action and technology framework aimed at optimizing the EuCauCA bioeconomy connectivity.

3 Methodology

Figures and statistics used in the study was taken from international reports mainly. Due to this approach, international agenda and EU principles on circular economy, digital transformation, data management and sustainability framework was largely used. Although the Caucasus and Central Asian countries are connected through some policy framework with European strategies, the implementation requires certain activities that was provided through extrapolation method for approximation and adaptation of processes.

Due to lack of data availability and quality in bioeconomy, the modeling of EuCauCA cooperation faces some difficulties. To avoid the distraction and data-gap, the model development was implemented through schematic design and text description of cooperation framework. This approach provides exact framework for data-based modeling and calculation of EuCauCA cooperation efficiency. The components included in the scheme are transferable into data and mathematical modeling.

The Global Gateway initiative, sustainable development principles and the approaches of the EU New Circular Economy Recourse Center are the main policy framework for developed methodology. Comparison, compliance and approximation between European experience and local needs of Caucasus and Central Asian countries to create common bioeconomy environment is the main type of cooperation discussed in the paper.

4 Results

According to the study, the role of the EU New Circular Economy Resource Center is pivotal in the cooperation between the Europe, Caucasus and Central Asia bioeconomy concept. There is assumed the EU circular and green economy frameworks as conceptual approach for bioeconomy cooperation modeling in EuCauCA strategical connectivity (Fig. 1).

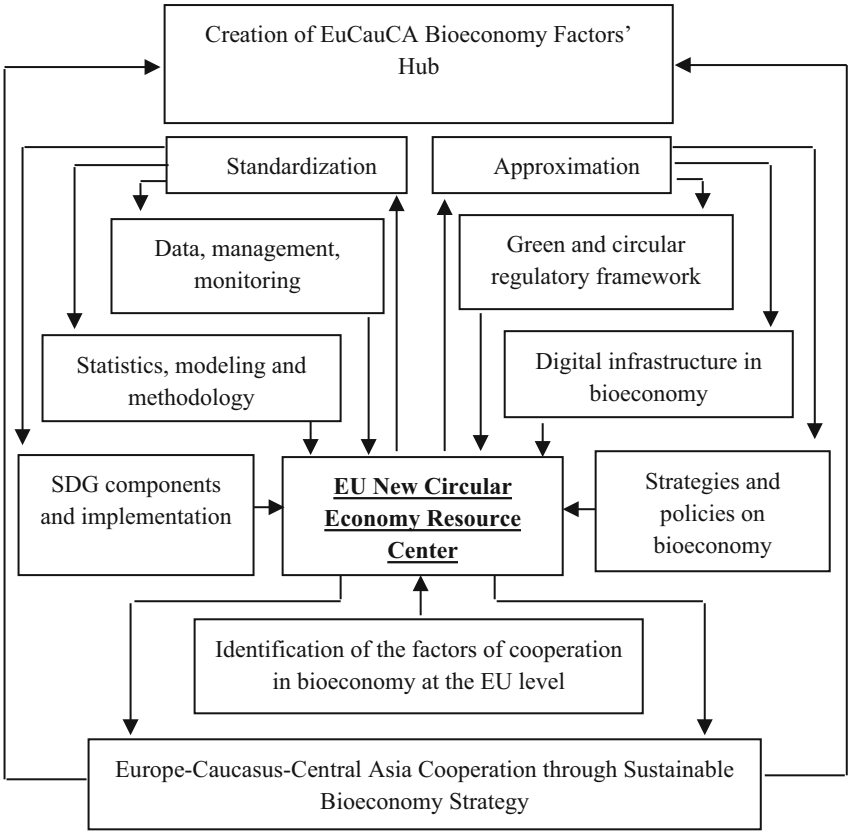


Fig. 1. The EU New Circular Economy Resource Center as a coordinating infrastructure in Europe-Caucasus-Central Asia bioeconomy cooperation

The Fig. 1. shows that data, statistics, SDG implementation indicators, digital infrastructure in bioeconomy, field-related strategies and regulations are the subject of standardization and approximation as fundamental factors of cooperation in the development of sustainable bioeconomy strategy. The interdisciplinary interoperability between economic, social and environmental indicators to standardize and approximate bioeconomy fundamental factors is the starting point of cooperation between the Europe, Caucasus and Central Asia, which is thoroughly explained in the model displayed on the Fig. 1.

The Europe, Caucasus, Central Asia cooperation in the framework of sustainable bioeconomy strategy is assumed identification of cooperation of factors in national levels of Caucasus and Central Asian Countries', as well as by EU. The Caucasus and Central Asian countries create Hub of Factors of cooperation related to bioeconomy in partnership with the EU New Circular Economy Resource Center. The factors should be categorized between "Standardization" and "Approximation" according to the nature of cooperation. The EU New Circular Economy Resource Center acts on behalf of both EU and the Hub of Factors created by the Caucasus and Central Asian countries.

The standardization and approximation components are formulated by the Hub of Factors and the EU New Circular Economy Resource Center. Standardized data, statistics and SDG implementation impact factors along with the approximated green and circular economy regulatory framework, digital infrastructure, strategies and policies on bioeconomy, are integrated with the EU New Circular Economy Resource Center to coordinate Europe-Caucasus-Central Asia cooperation in sustainable bioeconomy strategy in partnership with the Hub of Factors created in the Caucasus and Central Asian countries. Most of the factors of standardization and approximation are components of the EU Global Gateway initiative and the sustainable bioeconomy strategy in EuCauCA landscape will contribute the Global Gateway implementation. Business representatives and policy-makers of EuCauCA countries will be the main stakeholders of the Hub of Factors contributing through data, technology, compliance and regulatory to create common economic environment. Hub of Factors will serve as a connectivity toolkit to provide value-based and technology-driven institutionalization rather than physical infrastructure creation. This approach of institutionalization will be strong base for physical infrastructuralization initiatives.

5 Conclusion

The paper shapes policy framework of the EU green and circular economy initiatives to provide integration with Caucasus and Central Asia in the framework of bioeconomy. Practical implementation of cooperation through bioeconomy modeling can be a real impact test for European enlargement and neighborhood strategies expanding European economic area. Hub of Factors that is suggested to create in Caucasus and Central Asian countries, together with the newly established EU New Circular Economy Resource Center can be the main drivers of the standardization and approximation of data, statistics, methodology, indicators, digital infrastructure, strategies and regulations to promote cooperation.

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Regulatory Barriers and Opportunities for Rooftop Green Retrofit in Spain: Insights from the aRTes Project

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Abstract. Rooftop retrofits represent a strategic opportunity for urban climate adaptation, community resilience, renewable energy deployment and nature-based solutions (NBS). However, the regulatory structures governing these interventions remain fragmented in many European contexts. This paper analyses the Spanish regulatory landscape affecting rooftop retrofit within the Active RoofTops South Europe (aRTes) project. A multi-level approach is applied, examining European policy drivers, national building regulations, regional strategies and municipal planning procedures. The Spanish Building Code constitutes the primary binding technical basis governing rooftop interventions. Findings indicate that Spain lacks dedicated regulation for green roofs or rooftop farming systems. Rooftop retrofit is therefore assessed through existing construction, planning and technical regulations. This configuration generates several barriers, including structural compliance requirements for existing buildings, fragmented permitting procedures and administrative complexity within multi-owner residential buildings. The Spanish case illustrates how improved regulatory coordination and clearer administrative pathways could facilitate the integration of rooftop NBS within renovation policies, supporting decarbonisation and urban biodiversity enhancement.

Keywords: Rooftop retrofit · Green roofs · Urban farming · Regulatory barriers · Nature-based solutions · Photovoltaic systems

1 Introduction

Building rooftops are gradually integrated into European climate and energy policies as strategic spaces for climate adaptation, renewable energy deployment and urban resilience. Among the different rooftop-based strategies, nature-based solutions (NBS) such as green roofs and rooftop farming are incorporated into urban planning and climate programmes. Their potential to mitigate urban heat island effects, improve stormwater management and enhance urban biodiversity has been widely documented [1]. Rooftop green retrofit refers to the transformation of existing roofs through vegetated systems and/or renewable energy installations that contribute to climate mitigation and adaptation. The implementation of these measures remains conditioned by regulatory conditions governing building works in many countries.

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2 Methodology

This research is conducted as part of the Active RoofTops South Europe (aRTes) project, funded under the Driving Urban Transitions programme, which investigates how rooftops in Southern European cities can be activated through NBS, productive and renewable energy solutions. This work corresponds to Task 1.1, which reviews the regulatory landscape affecting rooftop retrofit interventions in Spain. The regulatory landscape is examined at multiple governance levels, including European policy instruments, national building regulations, regional strategies and municipal planning procedures. The analysis focuses on three rooftop retrofit technologies considered in the aRTes project: green roofs, urban farming systems and photovoltaic (PV) installations. The implementation of these solutions is assessed through several regulatory domains, including structural safety, waterproofing performance, energy regulation, planning constraints and property governance.

3 Multi-Level Regulatory Framework Governing Rooftop Retrofit in Spain

3.1 European Policy Drivers

Several policy instruments adopted under the European Green Deal reinforce the role of building renovation as a key mechanism for decarbonisation and climate resilience. Among the most relevant measures affecting rooftop retrofit are the recast Energy Performance of Buildings Directive (EPBD – Directive (EU) 2024/1275), the Energy Efficiency Directive (EED – Directive (EU) 2023/1791), the Nature Restoration Regulation (Regulation (EU) 2024/1991) and the recast Urban Wastewater Treatment Directive (UWWTD – Directive (EU) 2024/3019). Although these instruments do not directly regulate green rooftop technologies, they shape national renovation policies that promote the integration of renewable energy systems and urban green infrastructure. Their impact is primarily mediated through national legislation, renovation strategies and funding mechanisms adopted by Member States.

3.2 National Technical Framework

At the national level, rooftop retrofit interventions are governed mainly by the Código Técnico de la Edificación (CTE) [2], Spain's national building code. The CTE establishes performance-based requirements that apply to both new construction and renovation works through a set of Basic Documents (DB) addressing different technical domains. Rooftop retrofit projects may trigger several of these technical provisions depending on their characteristics. Structural verification requirements are defined in DB-SE (Structural Safety), fire safety provisions in DB-SI (Fire Safety), moisture protection requirements in DB-HS (Hygiene and Indoor Health), energy performance requirements in DB-HE (Energy Performance), and accessibility provisions in DB-SUA (Safety of Use and Accessibility).

Rooftop projects modify existing roof assemblies and may introduce additional loads or new rooftop uses; compliance with these requirements is therefore assessed on a case-by-case basis. Complementary technical regulations may also apply depending on the intervention type. For example, PV installations must comply with the self-consumption regime established by Royal Decree 244/2019 and with electrical safety requirements defined in the Reglamento Electrotécnico para Baja Tensión (REBT) [3].

3.3 Regional Planning Frameworks

Beyond national building regulations, Spain's autonomous communities (CCAA) shape rooftop retrofit through their competencies in urban planning, environmental policy and heritage protection. Regional instruments such as climate strategies, green infrastructure plans and territorial planning provisions support NBS, including green roofs and rooftop farming, while introducing complementary requirements affecting feasibility. These include land-use compatibility, volumetric and landscape integration criteria, environmental assessment procedures and heritage constraints. Such conditions may also affect rooftop PV systems where installations modify roof geometry or visual impact. As a result, regional variability can influence both administrative procedures and implementation conditions for rooftop retrofit projects.

3.4 Municipal Planning and Permitting Layer

At the local level, municipalities play a decisive role in determining the administrative feasibility of rooftop retrofit interventions. Municipal authorities are responsible for issuing building permits and ensuring compliance with local urban planning regulations established in instruments such as the Plan General de Ordenación Urbana (PGOU). Rooftop interventions are subject to municipal interpretation regarding their classification as minor or major works, which directly affects procedural requirements, documentation and approval timelines. Planning criteria related to volumetric limits, building height and visual impact may constrain rooftop uses where installations alter roof geometry, increase height or affect visibility. These factors are especially relevant for elevated structures such as PV installations or accessible rooftop spaces, and directly influence implementation pathways.

4 Regulatory Barriers to Rooftop Retrofit

4.1 Absence of a Dedicated Regulatory Category

A key regulatory challenge lies in the absence of a dedicated legal category specifically addressing rooftop retrofit interventions such as green roofs or rooftop urban agriculture. Regulatory requirements are therefore determined by the technical domains activated by each intervention. Structural verification requirements arise from the structural safety provisions of the Código Técnico de la Edificación (CTE), particularly DB-SE when additional loads are introduced. Waterproofing and drainage conditions are assessed under DB-HS, while fire safety provisions may be triggered through DB-SI depending

on rooftop accessibility and use. PV installations must additionally comply with electrical safety regulations established in the Reglamento Electrotécnico para Baja Tensión (REBT) and the national self-consumption framework.

This regulatory configuration creates interpretative uncertainty for designers, building owners and permitting authorities, as rooftop retrofit projects must navigate multiple regulatory domains without explicit technical guidance for rooftop NBS. In the case of rooftop urban farming, this complexity increases further, as productive use may activate additional regulatory requirements related to food safety and sanitary control when agricultural production is involved.

4.2 Technical Constraints of the Existing Building Stock

Another key barrier relates to the technical characteristics of the existing building stock. A large share of Spanish residential buildings was constructed prior to the introduction of the current building code framework in 2006, with approximately 45% built before 1981 [5]. These buildings may present structural or technical limitations affecting the feasibility of rooftop interventions. This condition represents both a constraint and an opportunity, as a large proportion of existing buildings potentially require renovation interventions where rooftop retrofit solutions could be integrated.

Structural capacity represents one of the most relevant constraints. Green roofs and rooftop farming systems introduce additional permanent loads associated with substrate layers, irrigation systems and vegetation. Ensuring compliance with structural safety requirements may therefore require detailed structural assessments and, in some cases, reinforcement measures. Waterproofing and drainage systems also represent critical technical considerations. Green roofs must ensure adequate moisture control and protection against water infiltration in accordance with the moisture protection provisions defined in DB-HS. In older buildings, existing roof assemblies may not have been designed to accommodate such systems, increasing the technical complexity and cost of retrofit interventions.

4.3 Administrative and Permitting Complexity

Beyond technical considerations, rooftop retrofit projects may face administrative barriers related to permitting procedures and regulatory interpretation at the municipal level. Municipal authorities are responsible for issuing building permits, but administrative interpretation may vary between municipalities, especially regarding the classification of rooftop works as minor or major interventions. This distinction affects the type of permit required, the documentation to be submitted and the administrative procedures governing project approval. In some cases, rooftop structures such as PV installations or green roofs may also be interpreted within planning regulations as elements affecting building volume or external configuration, potentially triggering additional planning requirements.

This variability in administrative interpretation may introduce uncertainty for project developers and influence approval timelines and procedural requirements. This complexity may also affect the implementation of publicly funded renovation programmes, including European recovery and renovation funding schemes.

4.4 Governance Constraints in Multi-Owner Buildings

Governance arrangements within multi-owner residential buildings represent an additional barrier to rooftop retrofit implementation. In Spain, shared building elements such as rooftops are typically governed under the horizontal property law (LPH – Ley de Propiedad Horizontal) [6], which regulates decision-making procedures within homeowners' associations. Rooftop retrofit projects involving shared roof spaces may therefore require collective approval from property owners according to the voting thresholds defined by (LPH). Achieving agreement among multiple property owners may be difficult when rooftop interventions involve financial contributions, perceived technical risks or changes in the use of shared building elements. As a result, governance constraints within homeowners' associations may limit the implementation of rooftop projects even where technical feasibility and regulatory compliance can be demonstrated.

5 Emerging Policy Opportunities for Rooftop Retrofit

5.1 European Regulatory Transition

The recast Energy Performance of Buildings Directive (EPBD – Directive (EU) 2024/1275) [7] establishes strengthened decarbonisation requirements for the European building stock. Several provisions may indirectly affect rooftop retrofit interventions, including the requirement for Member States to prepare National Building Renovation Plans (Art. 3 and Annex II), the introduction of Minimum Energy Performance Standards (Art.9) for the worst-performing buildings, and phased solar deployment obligations in buildings (Art. 10). These provisions reinforce the role of rooftop installations within compliance-oriented renovation strategies.

Similarly, the revised Energy Efficiency Directive (EED – Directive (EU) 2023/1791) [8] strengthens energy savings obligations and introduces binding renovation requirements for public sector buildings. These provisions may increase the number of building retrofit projects where rooftop-based solutions—such as PV systems or green roofs—can contribute to energy performance improvements. Environmental legislation introduces additional drivers relevant to rooftop retrofit. The recast Urban Wastewater Treatment Directive (UWWTD – Directive (EU) 2024/3019) [9] promotes integrated urban water management approaches, encouraging the use of green and blue infrastructure to mitigate urban runoff. Rooftop retention systems and green roofs may therefore contribute to stormwater management objectives in dense urban areas. In parallel, the Nature Restoration Regulation (Regulation (EU) 2024/1991) [10] establishes binding targets for urban ecosystem restoration, including provisions related to the maintenance and expansion of urban green infrastructure. These instruments reinforce the role of rooftop interventions within European climate and environmental strategies.

The implementation of European energy legislation often prioritises PV deployment in rooftop spaces due to its direct contribution to energy performance indicators. Rooftop NBS such as green roofs or rooftop agriculture remain less explicitly integrated within energy compliance schemes, despite their recognised contributions to climate adaptation, urban biodiversity and stormwater management.

5.2 National Renovation and Climate Policy Frameworks

At the time of writing, revisions to the Código Técnico de la Edificación (CTE) [4] are under consideration, including a proposed Basic Document on sustainability, together with the preparation of Spain's National Building Renovation Plan (PNRE/NBRP) [5] under the EPBD, which establishes long-term renovation trajectories aligned with European decarbonisation objectives. These developments may influence future regulatory conditions affecting rooftop retrofit interventions.

In parallel, national strategies such as the Integrated National Energy and Climate Plan (PNIEC) [11], the National Climate Change Adaptation Plan (PNACC 2021–2030) [12] and the National Green Infrastructure Strategy (ENIV) promote building renovation, climate resilience and urban NBS. Although these instruments do not define construction standards, they establish strategic priorities and funding mechanisms that may indirectly facilitate rooftop retrofit interventions. Within this policy landscape, green roofs and other rooftop-based solutions may be considered as complementary measures contributing to energy performance improvements, urban climate adaptation and biodiversity integration within the built environment.

5.3 Urban Policy Experimentation and Territorial Initiatives

At the municipal level, Barcelona has promoted green rooftops through the Pla del Verd i de la Biodiversitat and the Programa de Cobertes Verdes [13], which combine technical guidance, pilot projects and municipal incentives to encourage green roofs within urban climate adaptation strategies. These programmes frame rooftops as spaces for urban biodiversity enhancement and climate mitigation, and may also accommodate productive uses when integrated within broader green infrastructure policies. In Madrid, green roofs have been incorporated into urban planning instruments through the Factor Verde environmental performance parameter and the Plan Especial de Cubiertas Verdes [14], which introduce planning mechanisms aimed at encouraging green roofs within new developments and renovation projects.

In parallel, several municipalities have developed governance frameworks for urban agriculture through urban garden ordinances and programme-based initiatives. Cities such as Oviedo, La Laguna or Palma have established regulatory models defining allocation procedures, user eligibility and management conditions for community cultivation, which may be extended to rooftop contexts in public or collective buildings. Unlike green roofs, which are typically assessed as building-envelope systems, rooftop urban farming is regulated through land-use compatibility, activity classification and governance arrangements, increasing its dependence on municipal interpretation. These initiatives demonstrate how rooftop retrofit can be implemented through planning incentives and local governance mechanisms. They also highlight different pathways, with green roofs more integrated into urban policy tools, while productive uses depend more on land-use interpretation and governance structures.

6 Conclusions

Rooftop retrofit in Spain is not characterised by a lack of regulation but by a fragmented and multi-layered regulatory configuration in which different technical domains, planning instruments and governance structures overlap. This generates interpretative variability in retrofit scenarios that do not fit clearly within established categories of maintenance or major renovation. As a result, implementation depends less on the existence of regulation than on how existing provisions are interpreted and coordinated at different scales.

This regulatory structure produces differentiated implementation pathways. Green roof systems are generally assessed within building-envelope requirements and, in some cities, increasingly linked to planning regulations or environmental performance parameters. Their deployment remains constrained by structural uncertainty in existing buildings, competition with energy requirements and the absence of standardised technical criteria at national level. Rooftop urban farming presents a higher level of regulatory complexity, as it is not framed through construction standards but through land-use compatibility, activity classification and governance arrangements, making it highly dependent on municipal interpretation and community-based implementation models. In contrast, PV systems operate within a consolidated regulatory and incentive system aligned with European energy policy, which explains their faster and more homogeneous deployment despite similar structural and administrative constraints [15].

Current policy developments create a potential window for regulatory adjustment. The revision of the Código Técnico de la Edificación (CTE), the implementation of the National Building Renovation Plan and the broader European decarbonisation objectives reinforce performance-based requirements for building retrofit. These frameworks remain primarily oriented towards energy efficiency and renewable generation, with limited integration of green roofs within binding technical standards or energy performance metrics.

From a policy perspective, facilitating rooftop retrofit will require greater alignment between regulatory domains and rooftop technologies. This includes the development of clearer technical criteria for vegetated systems, whether through their stronger integration into the CTE or through at least a dedicated UNE technical standard for green roofs that reduces ambiguity in design, assessment and permitting, as well as a clearer regulatory framing for rooftop urban farming addressing land-use classification, health requirements and governance conditions. Bridging the current separation between architectural-scale regulation and urban-scale climate strategies is essential to ensure that rooftop interventions contribute coherently to decarbonisation and climate adaptation objectives. Aligning energy performance targets with biodiversity and green infrastructure objectives will be critical to avoid trade-offs between renewable deployment and ecosystem integration. More broadly, moving from isolated pilot initiatives towards coordinated, large-scale implementation strategies will be necessary to unlock the environmental potential of rooftop interventions within the existing building stock.

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Policy Frameworks and Digital Infrastructure to Accelerate Circularity and Whole-Life Carbon Reductions in the European Built Environment

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Abstract. Achieving a climate-neutral and circular built environment in Europe requires policy frameworks supported by robust data infrastructures, transparent governance models, and validated approaches that integrate circular technologies into renovation and construction practices. In that framework, the present paper presents a policy-oriented synthesis of the findings of two Horizon Eu-rope projects, DeCO2 and CRedIBlE, that operationalise whole-life carbon assessment, circular resource management, and interoperable building data systems along with harmonised data architectures with the aim to create the necessary conditions for policy instruments, that rely on accurate stock-level information.

Specifically, in the framework of those two projects, the paper will present a parametric evaluation of renovation measures to support the identification of cost-effective interventions compatible with circular design strategies. That framework can assist building users and managers in deciding on the best possible renovation strategies, material-reuse schemes, and carbon-reduction path-ways grounded in verifiable, comparable data. These capabilities are essential for implementing key policy levers, such as minimum energy performance standards (MEPS), digital building logbooks, and pre-demolition audit requirements. All in all, the research presents a technically rigorous yet policy-relevant framework for accelerating circular, low-carbon transformation across the European built environment.

Keywords: Circularity · Built environment · Whole life carbon assessment; energy

1 Introduction

The European building sector accounts for approximately 36% of the continent's total energy consumption and nearly 40% of its CO_2 emissions. The transition to a climate-neutral built environment by 2050 requires not only a massive acceleration in the rate of building renovation, but a fundamental shift in how buildings are designed, assessed, and decommissioned. This paper addresses these gaps by presenting a synthesis of findings

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from two Horizon Europe research and innovation projects: DeCO2 (Dynamic Decarbonization Pathways Framework: Integrating Technological, Social, and Policy Innovations for Sustainable Renovations in the Built Environment) [1] and CRedIBLE (Circular REDesign for a Resource-efficient, Innovative, and Transformative Built Environment) [2]. DeCO2 supports a circular and decarbonised built environment by delivering user-centric renovation solutions and demonstrating circular innovations, participatory approaches, policy guidelines, digital tools, and scalable Living Lab models. In parallel, CRedIBlE aims to accelerate circularity through an interoperable digital ecosystem, following a phased approach from design to deployment and capacity building. Together, the projects advance integrated approaches to whole-life carbon assessment, circular resource management, and interoperable data infrastructures across diverse European contexts.

2 Background and Policy Context

The European regulatory framework for the built environment has evolved significantly in the period 2020–2024, creating both unprecedented opportunities and substantial technical demands.

Circular Economy Action Plan (CEAP II, COM/2020/98) [3] identifies the construction sector as one of seven priority value chains, calling for material passports for construction products, a major reduction in construction and demolition waste, and the promotion of secondary materials in renovation and new build. Its emphasis, on both projects, is product-level traceability, secondary material markets, and design-for-disassembly directly aligns with the technical work.

The 2024 recast of the Energy Performance of Buildings Directive (EPBD) [4] represents the most ambitious update to EU building policy in over two decades. Its core provisions include the introduction of MEPS, requiring Member States to ensure that a defined proportion of the worst-performing building stock is upgraded to at least energy class E by 2030 and class D by 2033; the mandatory establishment of digital building logbooks for all new buildings and major renovations; and the requirement for pre-demolition audits on buildings above a defined floor area threshold prior to any significant demolition works. Each of these provisions generates specific data demands that existing national energy performance certificate (EPC) registries are ill-equipped to fulfil.

The Ecodesign for Sustainable Products Regulation (ESPR, Regulation EU 2024/1781) [5] aims to make sustainable products the norm in the European Union, expanding the earlier Ecodesign Directive beyond energy-related products to cover a broader range of categories with stricter sustainability criteria. ESPR imposes new obligations related to durability, recyclability, energy efficiency, and environmental impact disclosure. A central instrument of the ESPR is the Digital Product Passport (DPP), which provides detailed, accessible information on a product's sustainability performance, materials, and end-of-life instructions, ensuring more accountability throughout the supply chain.

The Construction Products Regulation (CPR, Regulation EU 2024/3110) [6] complements the ESPR. It adds mandatory climate indicators, introduces DPP for construction

products, and expands CE marking to include environmental performance, with priority categories. The DPP under the CPR acts as a unified platform for sharing environmental data verified according to EN 15804, the European standard governing Environmental Product Declarations (EPDs), and the updated Declaration of Performance must include Global Warming Potential data and other environmental characteristics expressed through standardised performance levels.

3 Methodological Framework

The integrated methodological framework developed by DeCO2 and CRedIBlE rests on three interconnected pillars (i) policy implications based on the analysed regulations above, (i) the use of Whole-Life Carbon Assessment (WLC) as a tool to measure circularity and (ii) the use of digital technologies to assess WLC requirements.

3.1 Whole-Life Carbon Assessment (WLC)

WLC assessment for buildings is defined by EN 15978:2011 [7] as the systematic quantification of the environmental impacts and aspects of a building system across its full lifecycle. The standard establishes a module-based framework encompassing the product stage (A1–A3), construction stage (A4–A5), use stage (B1–B7), end-of-life stage (C1–C4), and a beyond-the-system-boundary module (D) for reuse and recycling credits. EN 15804:2012 + A2:2019 [8] provides the corresponding product-level calculation rules for Environmental Product Declarations (EPDs), defining characterisation methods and system boundaries for individual construction products that feed into building-level calculations (for LEVEL(s) [9]).

Despite these normative foundations, WLC assessment in practice has been hampered by several structural limitations. Initially, the disconnect between design-phase LCA and operational performance monitoring. Second, BIM-LCA integration, while a growing area of research [10, 11], has remained largely manual: the extraction of quantity take-offs from BIM models for LCA input requires time-intensive, error-prone translation steps that deter routine practice. Furthermore, embodied carbon has received comparatively little systematic attention in European renovation practice, despite estimates that embodied carbon in construction accounts for approximately 10% of total annual global greenhouse gas emissions [12, 13]. Finally, conventional WLC approaches assume linear material flows and do not account for the carbon credits arising from material reuse or the circularity-adjusted embodied carbon charges that reflect secondary material substitution.

3.2 Digital Infrastructure and Interoperability

Building Information Modelling (BIM) has been widely identified as the most promising platform for automating the data collection that WLC assessment requires. Several academic and commercial tools have demonstrated BIM-LCA integration at varying levels of sophistication, but most remain limited to static, design-phase assessments without operational feedback loops. Additionally, Digital Twin technology extends BIM towards

continuous, real-time representation of a building's operational performance by integrating sensor data, IoT feeds, and simulation models into a dynamic, evolving model and enables calculation of operational carbon from actual monitored energy consumption rather than design estimates, substantially improving the accuracy and relevance of lifecycle assessment results for renovation decision-making. Finally, DPP provide the material-level data infrastructure to populate WLC calculations with verified embodied carbon data, tracking materials from production through use cycles to end-of-life across a distributed ledger or interoperable data platform.

4 Results

4.1 Policy Implications - Alignment Requirements and Policy-Data Nexus

DeCO2's whole-life carbon assessment framework, built on EN 15978 and EN 15804-aligned life-cycle accounting is precisely the type of verified, product-level carbon data that the CPR now mandates through its updated Declaration of Performance requirements; the parametric renovation model developed within DeCO2 directly consumes EPD-sourced carbon intensities for materials such as insulation and structural systems, meaning that CPR's push to standardise and expand EPD availability across priority construction product families will substantially improve the quality and coverage of the input data on which DeCO2's renovation scenario calculations depend.

CRedIBlE operationalises building data architecture and its federated digital building logbook. The pre-demolition audit protocols developed in CRedIBlE provide exactly the structured, machine-readable dataset that DPP-compliant supply chains will re-quire to demonstrate traceability and secondary material provenance. Table 1 maps the specific data requirements of DeCO2 and CRedIBlE. This mapping exercise reveals a high degree of complementarity between the two projects and demonstrates their collective capacity to meet the evidentiary needs of the emerging EU policy framework.

Table 1. Mapping of EU Policy Instruments to Data Requirements and Project Contributions

Policy Instrument	Data requirements	DeCO2 contribution	CRedIBlE contribution
EPBD (2024/1275/EU) — MEPS Art. 9	WLC performance standard; energy class floor for worst-performing stock by 2030/2033	CemBOX BIM-LCA digital twin: automated WLC (EN 15804) with real operational data; decarbonisation scenario comparison	BIM-to-LCA integration tools; AI-DSS compares renovation scenarios against MEPS thresholds; KPI framework for MEPS compliance

(*continued*)

Table 1. (*continued*)

Policy Instrument	Data requirements	DeCO2 contribution	CRedIBlE contribution
EPBD — Digital Building Logbook Art.	Mandatory logbook for new builds and major renovations; lifecycle data in interoperable digital format	Digital Building Logbook component within C-Toolbox; blockchain-backed material traceability; DeCO2 platform APIs for data integration	Digital ecosystem architecture connecting BIM, DPP, and LCA into unified logbook platform; GDPR-compliant modular architecture
EPBD — Pre-demolition audit	Material inventory and hazardous substance register mandatory before significant demolition	3D scanning using LiDAR/photogrammetry for pre-demolition material quantity assessment; circular material passport library	Integration of full material data into DPPs for traceability at deconstruction stage; selective deconstruction tested at Spanish pilot
CEAP II (COM/2020/98) — Material passports	Product-level data on composition, hazardous substances, and end-of-life options across lifecycle	Circular renovation material passports; material flow mapping with product-as-a-service model; EN 15804-aligned lifecycle carbon data	DPP framework: traceability, embodied carbon tracking, circular economy regulation compliance; tested across 6 pilot typologies
CEAP II — Circular construction products	Recycled content; recyclability at end-of-life; secondary material markets	Circular material portfolio: mycelium insulation, bio-based panels, recycled steel fibre, 3D-printed earth, ceramic robotic recycling;	CO2-storing, recycled, and low-carbon materials; secondary materials marketplace for HVAC, PV, solar components
CPR (EU 2024/3110) — EPD & DPP	Mandatory GWP disclosure via updated DoP; Digital Product Passports for priority categories from 2026	WLC data generated by CemBOX tool is EN 15804/EN 15978-aligned; material passports as verifiable digital datasets for CPR compliance	Full DPP framework design and implementation; linked to BIM and LCA for real-time environmental tracking; tested in residential, public, and academic buildings

(*continued*)

Table 1. (*continued*)

Policy Instrument	Data requirements	DeCO2 contribution	CRedIBlE contribution
ESPR (EU 2024/1781) — Digital Product Passport	Lifecycle traceability; sustainability performance; interoperability across supply chain actors	Material passports: cradle-to-end-of-life traceability; interoperable with CemBOX digital twin; policy framework for regulatory integration	DPP framework with standardised schema for construction materials; marketplace enabling secondary material trading compliant with ESPR principles

4.2 Whole-Life Carbon Implications

The parametric analysis shows that the most cost-effective WLC reduction pathways do not necessarily align with those maximising operational energy savings, revealing a structural bias in conventional assessments towards energy efficiency over embodied carbon and circularity. In this context, CRedIBlE provides a clear diagnosis of current limitations: although BIM–LCA workflows enable embodied carbon assessment, they often lack interoperability with Digital Twins, material passports, and real-time decision-support systems, while frameworks such as Level(s) and EN 15978 remain insufficiently operationalised for circular use cases. CRedIBlE addresses these gaps by developing an integrated digital ecosystem for material traceability and circular decision-making.

In parallel, DeCO2 tackles the "performance and design-to-market gap" by operationalising WLC as a central optimisation variable within a dynamic, data-driven framework that integrates circular material flows and real-time performance data into renovation scenarios. While CRedIBlE focuses on enabling data infrastructure and circular logic, DeCO2 translates these into actionable, investment-ready decisions.

Overall, the projects adopt complementary approaches: DeCO2 applies a top-down optimisation logic through digital twins, whereas CRedIBlE follows a bottom-up data integration approach centred on material-level information. Both align with EN 15978, but DeCO2 emphasises EN 15804 and Level(s), while CRedIBlE extends to-wards design for disassembly (ISO 20887) and Digital Product Passports. Together, they position WLC as a key bridge between policy, circularity, and data-driven building management.

Figure 1 illustrates the coverage of EN 15804/EN 15978 lifecycle modules across both projects using a four-level classification: DeCO2 exhibits a central emphasis on operational energy, supported by explicit coverage of product and construction stages (A1–A5) and addressed end-of-life stages (C1–C4). In contrast, CRedIBlE demonstrates a central focus on end-of-life stages (C1–C4), complemented by explicit targeting of Module D benefits and more implicit coverage of earlier lifecycle stages.

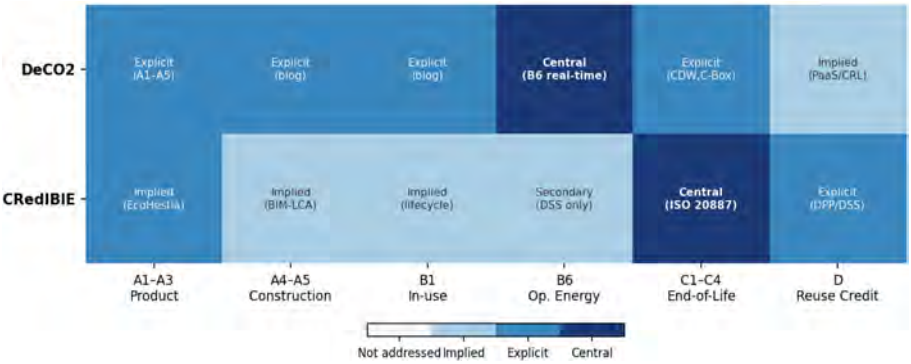


Fig. 1. EN 15804/EN 15978 Lifecycle Module Coverage in $DeCO_2$ and CRedIBlE

However, despite their differences, both projects converge on EN 15978 as the building-level normative standard and on the EU Level(s) framework as the overarching policy benchmark.

5 Discussion

The comparative analysis reveals that the field of WLC assessment for circular renovation currently lacks a unified methodological framework that integrates the operational energy performance strengths of energy-oriented digital twins (exemplified by DeCO2's CemBOX (digital twin) approach) with the material circularity and end-of-life tracking capabilities that circular economy frameworks require (exemplified by CRedIBlE's DPP-centred ecosystem). The convergence of both projects on BIM/IFC foundations, EN 15978 normative alignment, and embodied carbon within digital product passports suggests that such a unified framework is methodologically achievable; the remaining barriers are technical (module boundary standardisation, characterisation factor harmonisation, Module D methodology) rather than conceptual. Future research should prioritise the development of a reference methodology that formally specifies EN 15978 system boundaries for circular renovation scenarios, de-fines a shared EPD database for characterisation factors, and provides a transparent Module D credit calculation protocol consistent with both the projects outputs and the evolving CPR/ESPR regulatory requirements.

However, the analysis is only based on the results of the projects until now, DeCO2 in its second year, CRedIBlE in its first months, and subsequent public deliverables may resolve several of the open questions identified here.

6 Conclusions

This paper presented a comparative analysis of whole-life carbon (WLC) approaches in the $DeCO_2$ and CRedIBlE projects, highlighting a methodological divergence that is complementary rather than contradictory. $DeCO_2$ positions WLC as a central optimisation engine for renovation pathways, operationalised through a BIM–LCA digital

twin with explicit EN 15804/EN 15978 alignment and real-time data integration, supporting near-market, decision-ready applications. In contrast, CRedIBlE embeds WLC within a broader interoperable ecosystem focused on material circularity, prioritising embodied carbon, end-of-life stages, and Digital Product Passport integration, with a research-oriented focus on developing scalable data infrastructures.

The analysis identifies key methodological gaps, including lifecycle boundary definition, harmonisation of characterisation datasets, treatment of Module D benefits, and integration of real-time operational data. Addressing these gaps could enable a unified WLC framework that combines decision-oriented optimisation with advanced circular data infrastructures, directly supporting emerging EU regulatory requirements under the EPBD, CPR, and ESPR.

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The Role of Buildings in Local Climate Action Plans: A Comparative Analysis Between Brazilian Capitals and C40 Network Cities

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Abstract. The construction sector is fundamental to addressing climate change, and local plans are essential instruments for guiding the decarbonization process of buildings. This study evaluates how buildings are addressed in climate plans in Brazil and contextualizes them in relation to international plans. The methodology involved a rigorous literature review and the collection of documents from the climate plans of the 12 Brazilian capitals that currently possess such instruments (44.4% of the total capitals). Actions specifically aimed at buildings were systematically categorized and quantified. To establish a comparative basis, the C40 network was utilized as a sample universe, comprising cities committed to the climate agenda. Through cluster analysis (k-means algorithm), based on variables of population, area, and GDP, eight international cities with socioeconomic profiles analogous to those of Brazilian cities were selected, ensuring a relevant and representative comparative sample from all continents. The results of the national analysis indicate that actions related to buildings are scarce, representing between 5.6% and 23.0% (with an average of 9.8%) of the total strategies. These actions are predominantly generic, focusing on energy, water, and green infrastructure, with a prevalence of voluntary incentives but lacking specific targets and detailed implementation. The comparative methodological framework developed allows for the identification of learning potential from international practices, which highlight the need for more robust strategies. Finally, it is concluded that the approach to the building sector in the climate agenda is still incipient, and this study offers a pathway for the improvement of these plans.

Keywords: Construction Sector · Climate Change · Local Climate Action Plans · Buildings

1 Introduction

The global climate change scenario demands urgent action to achieve the goals of the Paris Agreement. In this context, the building and construction sector plays a critical role. In 2023, it was responsible for 34% of global CO_2 emissions and 32% of global energy

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demand, with operational emissions from buildings reaching a record high of 9.8 gigatons of CO_2 [1]. Despite its importance, the sector is not on track to achieve the goals of carbon neutrality and climate resilience by 2050 [1]. With slow and fragmented progress, the building sector will need to account for approximately 11% of the global mitigation potential by 2035, highlighting the need for more robust and effective strategies for decarbonizing the built environment [1].

Given this scenario, action at the local level is widely recognized as key to responding to the challenges of climate change [2]. Cities, as centers of human and economic activity, play a vital role in the climate agenda, and addressing the crisis depends directly on the urban and environmental policies adopted in this context [3]. In the Brazilian context, municipalities have legal support and constitutional powers to combat climate change, with the formulation of public policies, such as Climate Action Plans (CAPs), being the main way to address both the mitigation and adaptation agendas [3].

Despite the importance of buildings and the growing adoption of climate plans, the international literature suggests that urban climate adaptation planning often remains ineffective and lacks detail [4] [5]. While academic production in Brazil has increased, a gap persists in the understanding of the effective incorporation of the building sector into climate action plans. The literature lacks clarity on whether Brazilian local climate plans consider buildings as strategic elements for mitigation and adaptation, or whether the proposed actions are generic. This uncertainty hinders the advancement of effective public policies and the decarbonization of the built environment. To address this gap, this study makes three primary contributions. First, it develops a replicable methodological framework combining quantitative analysis of national plans with a qualitative, cluster-based comparison of international counterparts. Second, it provides the first quantitative benchmark—an average of 9.8%—for the building sector's weight within Brazilian climate plans. Third, it establishes a typology of climate actions for buildings, systematically categorizing the current strategic landscape. Thus, this study aims to critically assess the approach to buildings in the climate action plans of Brazilian capitals and contextualize it within international practices.

2 Methodology

This article employs a mixed-methods approach, combining quantitative and qualitative techniques. The research is based on document analysis and was structured in two main stages: (1) detailed analysis of the climate action plans of Brazilian capitals; and (2) comparative analysis with a set of international plans, selected through cluster analysis. The following sections detail each of these stages.

2.1 Stage 1: Analysis of National Plans

The first stage consisted of analyzing the climate action plans of Brazilian state capitals. State capitals were prioritized due to their political and administrative relevance, their greater technical and institutional capacity, and their role as a reference for other municipalities. Of the 27 state capitals, 12 had published climate action plans at the time of data collection (44.4%), and the sample therefore constitutes a complete census of

available plans, rather than a selection. These documents were obtained directly from the official websites of the respective city halls.

Thus, the document analysis was conducted in three sub-stages. In the first, each plan was examined to understand its structure and define the unit of analysis—the most detailed hierarchical level in each document—as an action, sub-action, or goal. For standardization purposes, these units were henceforth referred to as "items." In the second sub-stage, all items from each plan were analyzed, and those related to the building sector were identified and extracted to compose the research corpus. The inclusion criterion was based on whether the item directly referenced any phase of the building lifecycle, regardless of whether it also addressed other aspects beyond the building itself. Inclusion and exclusion decisions were made through discussion between two authors, ensuring consistency in the coding process. In the third and final sub-stage, the selected items were organized into two groups: (i) actions to be executed by the public authorities, subdivided into five subgroups (awareness and education; legislation and regulations; public policies; administrative actions; and practical actions); and (ii) actions to be executed by the population. Finally, both the quantification of the items, expressed as a percentage of the total of each plan, and the qualitative analysis of the content of each group/subgroup were carried out.

2.2 Stage 2: International Comparative Analysis

The second stage of the methodology aimed to contextualize the findings of the national analysis through a comparison with internationally recognized cities. To this end, eight cities from the C40 Cities Climate Leadership Group network were selected. The selection was performed using k-means cluster analysis in the Orange Data Mining software [6], with population, territorial area, and Gross Domestic Product (GDP) as input variables. The choice of these variables is justified by their being the main demographic and economic indicators highlighted by the C40 network itself for characterizing its member cities. Additionally, the selection process sought to ensure geographical representativeness, including metropolises from different continents.

The optimal number of clusters (k) was determined by the Silhouette Method, automatically calculated by the Orange software, adopting the value of k that maximized the silhouette coefficient for each region. This procedure resulted in $k = 2$ for America, Africa, Asia, and Europe, and $k = 3$ for Oceania. From the formed groupings, a single international city representative of each cluster containing Brazilian capitals was selected. The selection criterion followed a hierarchical logic: first, the absolute deviation of the population of each international city in relation to the population average of the Brazilian cities in the same group was calculated, and the one with the smallest deviation was chosen. In case of a tie, the same procedure was applied to the territorial area variable as a tie-breaker. In clusters where there was only one international city along with the Brazilian cities, this was automatically selected as it was the only comparative pair available. Clusters without Brazilian cities were disregarded. Thus, eight cities were selected: Lima [7] and Los Angeles [8], in America; Ekurhuleni [9] and Lagos [10], in Africa; Singapore [11], in Asia; Paris [12] and London [13], in Europe; and Sydney [14] in Oceania.

For the analysis of international plans, a qualitative approach focused on keyword searches was adopted. The terms "building" and "construction" were used to identify and extract the sections and actions directly related to the building sector in each plan. This method allowed mapping the main strategies and areas of focus of international cities, enabling a comparative discussion with the approaches identified in the Brazilian context. It is important to note that this international analysis is intentionally exploratory and qualitative in nature, designed to contextualize the Brazilian findings rather than to enable a direct statistical comparison between national and international plans.

3 Results and Discussion

The analysis of climate action plans across the 12 Brazilian capitals identified a total of 1,041 planning items. Of these, 102 items, representing an average of 9.8%, are directly related to the building sector. This quantitative finding establishes a crucial initial benchmark for assessing the sector's integration into Brazil's climate agenda. Significantly, the quantitative analysis (Table 1) also reveals substantial heterogeneity in the prioritization of the building sector among capitals, with figures ranging from a low of 5.6% in Belo Horizonte to a high of 23.0% in Rio de Janeiro.

Table 1. Analysis of items related to buildings in the Climate Action Plans of Brazilian capitals

Capital	Item	Total	Related items (%)
Belo Horizonte [15]	Sub-action	89	5,6%
Fortaleza [16]	Details	102	5,9%
Recife [17]	Details / Action	88	6,8%
Curitiba [18]	Action	38	7,9%
Teresina [19]	Sub-action	208	8,2%
João Pessoa [20]	Sub-action	119	8,4%
Rio Branco [21]	Strategic Action	58	10,3%
São Paulo [22]	Goal	59	13,6%
Salvador [23]	Sub-action / Action	100	15,0%
Florianopolis [24]	Line of Action	16	18,8%
Porto Alegre [25]	Priority Action	30	20,0%
Rio de Janeiro [26]	Climate Goal	74	23,0%

The 102 items related to the building sector were categorized into two main groups: (i) actions to be carried out by the public authorities and (ii) actions to be carried out by the population – Table 2. It should be noted that the same item may fall into more than one subgroup simultaneously, and due to this overlap, the total number of categorizations is 133 entries, of which 125 (94.0%) refer to actions by the public authorities and 8 (6.0%) to actions by the population. This predominance of state-led actions, concentrated

in "Practical Actions" and "Public Policies", reveals a structural tendency. Brazilian climate plans appear to prioritize direct interventions in public assets and the provision of voluntary incentives, often at the expense of robust, direct regulatory requirements for the private sector. Such a pattern inherently limits the scalability and transformative potential of decarbonization efforts within the built environment.

Table 2. Qualitative analysis of items related to the building sector in climate action plans

Group/Subgroups	Items	Predominant Themes
Awareness and education	16	Energy efficiency; solar energy; retrofitting; green infrastructure
Legislation and standards	23	Updating regulatory frameworks; energy efficiency; soil permeability; water management; embodied carbon; mobility
Public policies	31	Tax incentives; renewable energy; green infrastructure; social housing; rehabilitation of the built environment
Administrative actions	21	Management of public assets; consumption monitoring; planning and technical studies; process simplification; sustainable procurement
Practical actions	34	Energy efficiency and solar energy in public buildings; water management; social housing; embodied carbon; circular economy
Population	8	Renewable energy; sustainable materials; circular economy; electric mobility

To contextualize the national findings through an exploratory comparison, the climate action plans of the eight selected international cities were analyzed to identify actions and strategies related to the building sector. The depth of the approaches varies significantly: plans from Los Angeles, Singapore, and London include dedicated sections with quantitative targets and regulatory instruments, while those of Lagos and Ekurhuleni address the topic more broadly within energy strategies. The identified actions were compared with the 133 entries categorized in the Brazilian plans to identify convergences and gaps. Regarding convergences, both international and Brazilian plans align around leading by example in public administration — prioritizing solar energy installation and energy efficiency in public buildings — and the use of regulatory and incentive instruments for the private sector, such as revised building codes and tax incentives linked to sustainability certifications.

Other shared trends include encouraging the retrofitting of existing housing stock, adopting green infrastructure for heat mitigation, and sustainable water management. The integration of thermal comfort and resilience criteria in social housing also emerges as a point of convergence, signaling a common concern for climate justice. However, the comparative analysis reveals gaps in national plans, which are discussed to follow based on the identified international benchmarks.

In the field of financing mechanisms for retrofitting, international plans present more structured models. Singapore has consolidated the Zero Capital Partnership, in which energy performance contract companies fully finance the interventions, being remunerated by the savings generated in energy consumption. Ekurhuleni, in turn, retrofit debt to the property registration and uses an increase in property tax as a payment vehicle. Both models contrast with Brazilian plans, which depend on tax waivers or traditional credit lines and are still in the proposal phase - revealing a systemic barrier in mobilizing private capital for climate action at scale. Additionally, the London plan strategically addresses the landlord-tenant relationship to overcome the problem of split incentives—in which the landlord invests in the renovation, but the tenant benefits from the savings—a regulatory gap in Brazilian plans.

Another difference lies in the quantification of goals. While Paris sets a goal of renovating 100% of its buildings to very low-energy standards by 2050, at an annual rate of 40,000 housing units, and Los Angeles establishes targets for a 70% diversion of construction waste, Brazilian plans address these issues through guidelines and voluntary incentives, without setting percentage or scale targets for the private sector. Similarly, although they encourage the use of sustainable wood, national plans do not establish targets for the systemic replacement of concrete with bio-based materials. This absence of measurable commitments suggests a planning approach that prioritizes incentive-based instruments over regulatory requirements, hindering accountability and the ability to track progress.

Regarding structural resilience, international plans also go further than those proposed by Brazilians. London requires that new buildings be designed with specific infrastructure to withstand the impact of floods, an engineering requirement that goes beyond urban drainage. Sydney investigates the impacts of sea level rise on the integrity of foundations and proposes technical guidelines for the adaptation of underground structures. While Brazilian plans identify these risks, they are still in the diagnostic and monitoring phase, without advancing to the regulation of specific engineering solutions. Sydney also treats preventive maintenance of roofs and gutters as a public policy for climate adaptation, a topic absent from Brazilian plans.

Finally, technological and regulatory innovations in international plans not yet considered in Brazil are identified. Singapore presents specific actions for the modernization of elevators with energy regeneration systems, a roadmap for energy efficiency in data centers, and the implementation of pneumatic waste collection systems in high-density areas. Paris, in turn, establishes a mandatory Summer Comfort Index for new constructions, with more stringent internal temperature standards than national norms. Such actions represent a level of technical and regulatory specificity that can serve as a reference for the next generation of climate plans in Brazil.

4 Conclusion

The building sector is recognized as one of the main emitters of greenhouse gases in cities, with a direct impact on energy consumption, water resources, and waste generation. In this context, this study found that, on average, 9.8% of the items in the climate action plans of Brazilian capitals are associated with the sector — a figure

that establishes a novel benchmark for future monitoring and suggests that buildings have the potential to gain greater centrality in these planning instruments. The results also reveal that current actions are predominantly generic and reliant on soft policy instruments, pointing to a significant gap between planned strategies and the regulatory instruments required for effective decarbonization. This finding suggests that future plans should move beyond voluntary frameworks and incorporate binding targets, mandatory standards, and innovative financing mechanisms as core policy instruments

The scientific contribution of this study is threefold. First, it develops a replicable methodological framework combining cluster analysis with qualitative and quantitative document analysis — a model that can be expanded to a larger number of cities or applied to other sectors. Second, it provides a novel quantitative benchmark for the building sector's weight in Brazilian climate plans. Third, it establishes a typology of climate actions that maps the prevailing policy instruments and identifies structural gaps.

However, this study has limitations inherent to its documentary nature: it analyzes what the plans foresee, not what is actually implemented, without data on budgets, enacted regulations, or emission reductions achieved. Therefore, it cannot be concluded that plans with a higher density of actions necessarily yield better practical outcomes. The assessment of implementation constitutes a natural continuation of this research agenda, beyond the scope of the present study.

Finally, the analysis identifies a range of international practices that offer a valuable set of references, warranting in-depth feasibility studies to assess their applicability to the Brazilian context and thereby contributing to the maturation and effectiveness of future national climate plans.

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Renovate, Don't Erase: A Retrofit-First Perspective on the Existing Building Stock in Belgrade

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Abstract. Existing building stock in Belgrade is increasingly treated as an expendable obstacle to urban development, even though current European policy frameworks promote a "renovate first" approach and the circular use of existing buildings. Relying on analysis of European Union and Serbian legislation, local planning documents, heritage and policy reports, and public narratives, the study reconstructs how such buildings have been framed as obsolete, and how options of repair, adaptive reuse, and partial transformation have been marginalised or left institutionally under-specified. The paper adopts a retrofit-first hierarchy for decision making, in which preservation and adaptive reuse of existing structures and their material fabric are primary, limited selective removal and component recovery are secondary, and full demolition is recognised as a last resort. The analysis reveals a persistent misalignment between this hierarchy and the regulatory and planning practices through which redevelopment is currently justified. The paper contributes to debates on circular construction and urban transformation by showing that retrofit-first in this context is not only an environmental and technical question, but also a matter of governance, legal interpretation, and cultural value.

Keywords: Retrofit-First · Adaptive Reuse · Circular Built Environment · Existing Building Stock · Modernist Heritage

1 Introduction

The climate emergency and growing pressure on resources have intensified criticism of demolition-led urban development and renewed attention to the existing building stock as a material, environmental, and cultural resource. Recent European policy frameworks increasingly treat the existing building stock as a strategic resource and connect renovation with circularity, life cycle thinking, and decarbonisation goals [1–3].

In Serbia, circular economy and building renovation have entered the policy field through strategic and regulatory documents, but their application to existing building stock remains less clearly articulated. Related documents introduced these priorities into the national policy framework, while the legal and regulatory treatment of buildings continues to depend on a broader set of planning, construction, energy, and heritage instruments [4].

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The paper examines what a lack of retrofit-first perspective means in the case of three large modernist complexes in Belgrade: The General Staff Headquarters complex (hereafter Generalštab), the Belgrade Fair complex, and Hotel Yugoslavia. Its focus is not a technical comparison of demolition and renovation scenarios, but the regulatory and institutional conditions under which such decisions are made. By comparing selected EU and Serbian policy documents and relating them to these cases, the paper argues that the weak position of renovation, adaptive reuse, and material retention in contemporary Belgrade building practice is not only an environmental and technical issue, but also a matter of governance, legal interpretation, and cultural value.

2 Methodology

This paper adopts qualitative research based on comparative document analysis and interpretive case commentary. It examines selected European Union and Serbian policy and legal documents relevant to existing building stock, renovation, circularity, and heritage protection. The analysis focuses on how these documents frame renovation and adaptive reuse, whether they introduce life cycle and circularity considerations, and to what extent they support retention over demolition in decision making.

Based on the results of the analysis, three Belgrade cases, the Generalštab complex, the Belgrade Fair complex, and Hotel Yugoslavia were considered, as contrasting examples of different protection histories, planning treatments, and redevelopment trajectories. These cases were selected not because they are identical, but because together they reveal how different institutional and planning conditions influence whether existing buildings are retained, transformed, or replaced.

3 Literature Review and Policy Context

Buildings account for a large share of global material and energy consumption, while also generating a substantial proportion of global solid waste [5]. Therefore, research on circularity in the built environment emphasises strategies such as design for life extension, durability, adaptability, design for disassembly, reuse, repair, remanufacturing, and recycling to extend service life and reduce waste. However recent systematic reviews indicate that the application of circular economy principles across the construction sector is still limited and that several aspects of implementation remain under-researched [6, 7].

3.1 EU Policy Drivers

The European Green Deal sets climate neutrality by 2050 as a central strategic objective and frames circular economy measures as part of the broader transformation of the European economy [8]. Current EU strategic documents, action plans and directives advocate the idea of achieving climate neutrality by 2050 and frame circular economy measures as part of a broader transformation of the European economy. Construction and buildings have been identified as a priority area, promoting greater resource efficiency,

the circular use of materials and improved durability and adaptability of built structures [1–3].

Rather than establishing a direct prohibition on demolition, these documents collectively signal a policy shift toward the renovation of existing stock, the reduction of operational and embodied impacts, and the closer integration of circular principles into building regulation.

3.2 Serbian Legal Framework and Circular Economy Initiatives

Serbia, as an EU candidate country, has gradually incorporated circular economy and energy efficiency into its strategic and regulatory framework, although this process remains partial and uneven. Circular economy concepts are introduced into the national policy field, stressing the need for cross-sectoral coordination, regulatory adjustment, and the development of supporting market mechanisms [4].

The more relevant framework for this paper lies at the intersection of planning, energy, construction, and heritage protection. The Law on Planning and Construction provides the general legal basis for planning, development, and construction processes, while the long-term renovation strategy to 2050 establishes the principal policy framework for building renovation [9, 10]. Regulations regarding energy efficiency and energy certification of buildings remain important implementation instruments, but they are primarily oriented toward operational energy performance and technical compliance [11, 12]. In the case of construction products, national regulation aligns more closely with European standards, yet it does not by itself establish a hierarchy of retention, reuse, selective removal, and demolition [13]. Finally, the Law on Cultural Heritage imposes that decisions on existing buildings depend not only on energy and construction requirements, but also on how heritage value and protection status are defined, maintained, or revised through administrative procedures [14].

Although these measures indicate partial alignment with broader European sustainability agendas, the Serbian framework remains fragmented across sectors. Recent research has also highlighted the relevance of applying circular economy principles to the reconstruction and adaptation of buildings, particularly through durability, adaptability, waste reduction, and more integrated implementation of legislation and policy [15]. Even so, the Serbian framework still does not provide a sufficiently explicit decision structure for weighing adaptive reuse, deep renovation, partial transformation, and demolition where these objectives come into conflict.

3.3 Research Gap

A comparison of the selected EU and Serbian policy documents reveals not merely the existence of two separate regulatory frameworks, but a substantive difference in how renovation, circularity, and life cycle thinking are articulated and operationalised. Despite growing interest, most Serbian research on retrofitting existing buildings focuses either on technical energy saving measures or on economic feasibility. Few studies adopt a broader lens that integrates legal, socio cultural, and governance dimensions. At the same time, the national legal and policy framework does not provide sufficiently clear criteria for deciding between deep renovation, adaptive reuse, partial transformation,

and demolition, nor does it systematically account for embodied carbon, material reuse potential, and cultural value.

Table 1. Comparative policy table for circular retrofit and retrofit-first decisions

Document	Existing stock explicitly addressed	Renovation explicitly promoted	Circularity and lifecycle considerations	Clear decision support for retention over demolition
Law on Planning and Construction	Defines existing buildings and adaptation/reconstruction as works on them.	Enables adaptation and reconstruction interventions on existing buildings.	Demolition permit may require construction waste management plan documentation.	If hazard removable by reconstruction, authority orders it before demolition.
Circular Economy Roadmap (2020)	Identifies residential buildings as 75% of stock; promotes efficiency upgrades.	Recommends adaptation and reconstruction of buildings under circular, zero-waste principles.	Frames construction as "material bank"; promotes reuse and recycled-content targets.	Addresses demolition mainly as waste; no retention-over-demolition decision criteria.
Directive (EU) 2024/1275 (EPBD)	Requires national renovation plan to transform existing buildings into zero-emission.	Introduces renovation passports; voluntary for owners unless Member State mandates.	Mandates life cycle GWP calculation and disclosure in EPCs for new buildings.	Planned demolition may justify exemptions from MEPS; no retention rule.
Circular Economy Action Plan	Addresses buildings' life cycle impacts; links construction and renovation to emissions.	Promotes durability/adaptability and Renovation Wave alignment with circular principles.	Calls for LCA via Level(s), recycled content, and higher C&D recovery.	No retention criteria; focuses on circular design and demolition-waste management.

As shown in Table 1, the main difference lies not only in terminology, but in the extent to which these issues are translated into clearer decision-making criteria.

4 Modernist Heritage Between Protection and Redevelopment: Comparative Commentary

The presented case studies were selected not because they share the same legal status or planning trajectory, but because together they reveal how different forms of heritage recognition, institutional treatment, and public significance shape the fate of major modernist complexes in Belgrade. All three cases have long occupied a significant place in the spatial identity and collective memory of Belgrade and have each generated public criticism and professional resistance to their transformation or loss.

Generalštab on Kneza Miloša Street has become the most visible recent example of conflict between heritage protection and redevelopment interests in Belgrade. In

November 2025, a proposed *lex specialis* sought to suspend the ordinary application of Serbia's heritage and environmental legislation for this site to facilitate a large hotel and real-estate redevelopment project. International and domestic professional organisations argued that these moves not only bypassed regular legal procedures but also relied on the earlier contested removal of the site's protected status, which had already triggered legal and institutional controversy. Furthermore, despite the damage caused by the 1999 NATO bombing, the complex had repeatedly been recognised as suitable for revitalisation rather than demolition [16]. In this case, the language of danger and ruin did not emerge from a transparent comparison of retrofit, adaptive reuse, and demolition scenarios, but was instead used to legitimise the weakening of legal protection and the advancement of redevelopment transformation.

The Belgrade Fair complex was one of the key spatial and architectural expressions of Yugoslavia's modernist ambitions. Its significance lies not only in its urban and architectural value, but also in the engineering importance of its large-span halls, most notably Hall 1. Its protection history reveals early institutional inconsistency: in 2009, the ensemble was granted protection, but it was immediately partially de-listed, leaving only Hall 1 under formal heritage protection [17, 18]. More recently, the complex became entangled in the expansion of the Belgrade Waterfront planning area, where draft planning changes opened the possibility of demolishing most of the fairground despite strong professional and public opposition [19]. Only later did the planning process shift toward defining Halls 1, 2, and 3 and the administration building as a public-use complex, while leaving the future treatment of the existing structures to be reassessed through an architectural and urban planning competition [18].

Hotel Yugoslavia, completed in 1969, embodied the representative ambition of late Yugoslav modernism and long functioned as one of the most recognisable landmarks of New Belgrade. Its trajectory differs from the previous two cases because demolition has already taken place. The building remained listed as a property under prior protection until late 2011, when it was removed from the register of assets eligible for protection [20]. After decades of decline following the damage sustained during the 1999 NATO bombing, demolition began in November 2024 and was already well advanced by January 2025, with redevelopment of the site proceeding thereafter [21]. Not only was the building lost, but also no clear and transparent institutional obligation required adaptive reuse to be seriously tested against replacement before demolition moved forward.

As shown in Table 2, analysed buildings nevertheless differ in the degree and stability of protection, the presence or absence of war damage, the physical condition of the structures, and the type of value attributed to them. These differences help explain why similar calls for retention, repair, or adaptive reuse were translated into different institutional outcomes.

Table 2. Comparative overview of the three Belgrade cases

	Generalštab	Belgrade Fair	Hotel Yugoslavia
			
Built	1955–1965 [22]	1954–1957 [17]	Completed 1969 [20]
Protection regime and its transformation	Cultural monument since 2005; entered central register in 2006; protection later revoked; *lex specialis* proposed to enable exceptional redevelopment treatment [22]	Entire complex protected in January 2009; protection quickly narrowed; only Hall 1 retained durable protection as a cultural monument from February 2009, entered in the central register in 2010 [18]	Under prior protection until 24 Dec 2011; then removed from the relevant evidence, without transition to a stronger heritage regime [20]
Physical condition	Damaged in the 1999 NATO bombing; considered suitable for revitalisation [16]	Structurally viable complex: large-span halls retain major architectural and engineering significance [17]	Western wing damaged in the NATO bombing of 1999; later neglected; remained a recognisable urban structure [20]
Outcome	Redevelopment pressure intensified; *lex specialis* proposed; outcome remains unresolved [16]	Demolition scenarios opened; partially revised through later planning changes; broader retention re-entered the process [18, 19]	Demolition began on 15 Nov 2024; building gone in 2025 [21]

5 Discussion and Conclusion

The comparison of EU and Serbian policy documents shows not simply a difference in regulatory scope, but a more substantive difference in how existing building stock is understood. In the EU framework, renovation, circularity, and life cycle considerations are more explicitly linked to the transformation of the built environment. In current

Serbian practice, by contrast, these priorities are recognised across several policy fields but remain fragmented and only weakly translated into clear decision-making criteria for existing buildings.

The three Belgrade cases emphasise how this institutional weakness operates in practice. Although they differ in legal status, planning treatment, and outcome, all three indicate that retention, repair, and adaptive reuse are not consistently subjected to serious comparative assessment before redevelopment advances. In the Generalštab case, the language of danger was used to support the weakening of protection. In the Belgrade Fair case, retention re-entered the planning process only belatedly and within an unstable redevelopment scenario. In the Hotel Yugoslavia case, demolition proceeded without any clear obligation to demonstrate why adaptive reuse was no longer viable.

The central problem lies in the weak institutional articulation of retention, adaptive reuse, and material value within Serbia's planning and heritage framework. The key issue is therefore not only whether individual buildings are protected, but whether the institutional framework provides clear criteria for treating existing building stock as a cultural and material resource before demolition becomes the dominant trajectory.

The analysed case studies show that retrofit-first principle is not only an environmental and technical question, but also as a question of governance, legal interpretation, and cultural value. In this sense, the treatment of existing building stock in Belgrade remains shaped less by transparent evaluation than by discretionary and redevelopment led decision making. More broadly, the paper suggests that, without stronger institutional support for the continued use and transformation of existing buildings, the alignment between Serbian practice and wider European renovation and circularity agendas will remain partial and unstable.

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Public Procurement for a Circular Built Environment: Making the Case for Innovative Approaches and Assessment Techniques

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Abstract. Public procurement has the potential to accelerate the transition toward circular buildings by incentivising sustainable design, construction, and operation across the lifecycle of built assets. This paper explores innovative procurement approaches and assessment techniques that support the objectives of the European Green Deal and the Circular Economy Action Plan, which identify construction as a priority sector for circular transition. Special attention is given to Life Cycle Sustainability Assessment (LCSA), which integrates environmental, economic, and social dimensions when evaluating circular building solutions. While Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are increasingly applied in procurement processes, the assessment of social impacts remains challenging due to methodological limitations and lack of standardized indicators. Through a comparative analysis of European public procurement practices, particularly the Dutch approach, the study identifies mechanisms for embedding circularity criteria into public tenders. The findings demonstrate how procurement can stimulate markets for low-carbon, circular, and innovative construction solutions. The paper concludes with policy recommendations aimed at strengthening lifecycle-based decision-making, improving transparency, and supporting systemic transformation toward a circular built environment.

Keywords: Circular Buildings · Public Procurement · Life Cycle Sustainability Assessment (LCSA) · Assessment Techniques · Circular Economy · Policy Innovation

1 Introduction

Public procurement represents one of the most powerful policy instruments for accelerating the transition toward a circular and sustainable built environment. With purchasing power representing approximately 14% of the European Union's (EU's) gross domestic

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product (European Commission, n.d.), public authorities significantly influence market demand for sustainable products, services, and construction solutions. The EU Public Procurement Directive 2014/24/EU established a legal framework enabling contracting authorities to integrate environmental, social, and innovation criteria into procurement procedures through the most economically advantageous tender (MEAT) approach. In addition, the directive encourages the use of life cycle costing (LCC) to evaluate the total costs of works, goods, or services over their entire lifecycle rather than focusing solely on upfront price (European Commission & ICLEI, 2016).

Recent EU regulatory developments further strengthen lifecycle-based decision-making in construction. The revised Construction Products Regulation (EU) 2024/3110, together with the EN 15804 standard, promotes lifecycle-based environmental information through Environmental Product Declarations (EPDs). At the same time, broader EU policy initiatives such as the European Green Deal, the Circular Economy Action Plan (CEAP), the EU Taxonomy, and the Corporate Sustainability Reporting Directive (CSRD) increasingly position public procurement as a key driver of the circular transition.

Within this policy landscape, the Level(s) framework developed by the European Commission provides a harmonized methodology for assessing environmental impacts, resource efficiency, and circularity performance of buildings. These indicators allow contracting authorities to translate sustainability objectives into procurement requirements such as life cycle carbon assessment, material reuse targets, and construction and demolition waste recovery rates. In practice, the framework supports the development of measurable tender criteria and performance monitoring across the building lifecycle.

Consequently, public procurement is gradually evolving from a price-driven administrative procedure toward a strategic instrument capable of stimulating innovation, supporting circular business models, and accelerating the transformation of the built environment.

This paper aims to examine how lifecycle-based assessment techniques can be integrated into public procurement processes in order to support circular construction practices.

2 Conceptual Framework: Circular Public Procurement and Lifecycle Techniques

The procurement of circular buildings requires evaluation approaches capable of addressing sustainability across the entire building lifecycle. Over time, several lifecycle assessment techniques have emerged, each addressing different dimensions of sustainability (Fig. 1).

Life Cycle Analysis or Life Cycle Assessment (LCA) evaluates environmental impacts associated with all stages of a product or building life cycle, from raw material extraction and manufacturing to construction, use, and end-of-life processes. Life Cycle Costing (LCC) evaluates economic performance by accounting for capital costs, operation, maintenance, renovation, demolition and disposal costs across the building life cycle (UNEP/SETAC Life Cycle Initiative, 2011).

A complementary approach, Social Life Cycle Assessment (S-LCA), aims to assess social and socio-economic aspects of buildings and their potential positive and negative impacts along their life cycle (UNEP/SETAC, 2009). Integrating these dimensions leads to Life Cycle Sustainability Assessment (LCSA), which combines environmental, economic, and social considerations into a holistic decision-making framework (UNEP/SETAC Life Cycle Initiative, 2011) aimed at promoting more sustainable buildings throughout their life cycle.



Fig. 1. Life cycle techniques. *Note.* AI-generated image based on information provided by the authors.

Despite growing policy support, many contracting authorities still face practical challenges in implementing life cycle approaches in procurement processes. Limited expertise, lack of standardized tools, and fragmented data often prevent systematic application of LCA and LCC methods. In France, green public procurement (GPP) is hindered by insufficient resources and expertise to carry out life cycle costing and to systematically measure environmental externalities (OECD, 2024a). However, France promotes innovation and circularity in building procurement by embedding minimum recycled material requirements and sustainability targets in law, setting material reuse criteria in tenders, and supporting innovative regional projects that combine circular economy principles with social and environmental performance. These efforts help shift procurement away from purely cost-driven decisions toward lifecycle-oriented and circular solutions within the construction sector. As highlighted in the OECD (2024a) review of green public procurement practices, public authorities frequently struggle with insufficient technical capacity, limited life cycle data, and institutional barriers related to budget constraints.

Another persistent challenge relates to the separation between capital investment budgets and operational budgets, which discourages procurement decisions involving higher upfront costs even when long-term savings are significant (Dodd, Garbarino &

Gama Caldas, 2016). As a result, procurement decisions often remain dominated by purchase price rather than life cycle value.

Nevertheless, lifecycle-based procurement offers clear advantages. By accounting for energy consumption, maintenance costs, and end-of-life disposal, LCC can reveal that sustainable building solutions often deliver lower total costs over time, while simultaneously reducing environmental impacts. Additionally, circular design approaches such as Cradle-to-Cradle (C2C) further strengthen lifecycle thinking in construction. C2C buildings are designed to minimise environmental impacts throughout their life cycle by reducing greenhouse gas emissions, improving resource efficiency, and limiting waste generation. The concept also promotes circular economy principles by enabling the reuse and recycling of building materials, transforming buildings into "material banks" whose components can be recovered or repurposed at the end of their lifecycle. In addition, C2C principles emphasize healthy materials and biodiversity integration, contributing to improved indoor air quality and enhanced quality of life for building occupants (Upcyclea, 2023).

3 Integrating Green, Circular and Social Public Procurement

European policy frameworks increasingly emphasize the integration of environmental, social, and circular criteria within procurement practices (Fig. 2). Circular procurement extends beyond environmental performance by also addressing social objectives such as fair labour conditions, supply-chain transparency, community benefits, and occupant well-being. By incorporating these criteria into tender specifications and award evaluation procedures, public authorities can ensure that circular solutions deliver broader societal benefits alongside environmental improvements (EIB, ICLEI Europe, Circle Economy, 2025).

However, the implementation of sustainable procurement requires significant institutional capacity. Procurement officials often lack training, tools, and data necessary to apply complex lifecycle methodologies and evaluate sustainability criteria effectively (OECD, 2024a). Public authorities should therefore increasingly adopt the role of "intelligent clients", relying on external expertise, market engagement, and innovative procurement mechanisms to support sustainability objectives (SCI-Network, ICLEI, 2012). Early market engagement, public-private partnerships, and performance-based procurement approaches have proven effective in encouraging innovation and sustainability in infrastructure projects.

For example, the Cleveleys coastal project completed in 2010 in the United Kingdom successfully integrated sustainable infrastructure solutions with community regeneration objectives. The project combined sea defence infrastructure protecting approximately 7,700 homes with a low-carbon seaside resource for residents and visitors, thereby improving public space. Developed through close consultation with the community, the 1.3 km coastal development includes sustainable features such as helical wind turbines generating energy and LED lighting along the promenade. Early market and supply-chain engagement helped deliver the project ahead of schedule and below budget while creating around 150 local jobs and stimulating regional economic activity by establishing a concrete factory that continues to employ staff (SCI-Network, ICLEI, 2012).



Fig. 2. Sustainable public procurement. *Note.* AI-generated image based on information provided by the authors.

The tenders present an opportunity to encourage companies and workers to develop circular skillset by embedding requirements for past experiences and training clauses (EIB, ICLEI Europe, Circle Economy, 2025). Public procurement procedures can also promote circular construction by requiring certifications such as C2C Certified®, Leadership in Energy and Environmental Design (LEED), or Building Research Establishment Environmental Assessment Method (BREEAM) within tender specifications. Such requirements encourage contractors to adopt circular construction practices and achieve the intended sustainability objectives (EIB, ICLEI Europe, Circle Economy, 2025).

Nevertheless, the implementation of LCSA remains limited. Most procurement frameworks still focus primarily on environmental LCA and economic LCC indicators, while social lifecycle impacts remain less standardized and difficult to quantify. Potential social indicators include occupational health and safety, labour conditions, local employment generation, and occupant well-being; however, their integration into procurement remains constrained by limited data availability and lack of harmonized assessment methodologies.

4 The Dutch Approach to Public Procurement in Construction

Among European practices, the Netherlands represents one of the most advanced and operationalised examples of lifecycle-based public procurement in construction. A key instrument determining the winning bid in Dutch infrastructure procurement is the Environmental Cost Indicator (ECI), which translates environmental impacts quantified using LCA into monetary values expressed in euros. The ECI reflects the environmental "shadow price" of materials and construction activities, enabling objective comparison between alternative design solutions and environmental performance of different contractors.

Contractors submitting bids with lower ECI scores receive a higher fictional discount during tender evaluation, improving their competitiveness. This mechanism incentivizes

contractors to propose solutions with lower environmental impacts, thereby integrating sustainability directly into procurement decision-making (Hillege, 2019). The ECI is widely used by public authorities to integrate sustainability into tendering, by contractors to evaluate the environmental impacts of design and execution options, and by policymakers to translate climate and circularity goals into concrete actions in infrastructure projects (Nationale Milieudatabase, n.d.).

The ECI calculations rely on data from the Dutch National Environmental Database (Nationale Milieudatabase, n.d.) and are supported by validated calculation tools that integrate environmental product declarations and lifecycle data. These tools allow contractors to evaluate material impacts, carbon emissions, and circularity performance during project design. Moreover, they enable the material passport to be used as evidence for subsidy programs such as MIA/Vamil and ensure circular construction and BREEAM credits by integrating all legally required and industry-recognized calculation methods and databases (BCI, n.d.). From 2025 onward, ECI methodology is progressively aligned with EN 15804 + A2 standards, expanding environmental assessment to 19 impact categories and improving lifecycle impact comparability. In addition, the Netherlands requires the calculation of the Environmental Performance of Buildings (MPG) for new buildings. This metric expresses environmental impacts in euros per square meter of gross floor area per year, with lower values indicating better sustainability performance. While the ECI approach primarily evaluates environmental lifecycle impacts, Dutch social procurement objectives are generally addressed through separate policy instruments and tender criteria rather than being integrated into the ECI methodology itself (PIANOo, n.d.; OECD, 2024a).

The Dutch government also promotes circular innovation through initiatives such as the Startup in Residence programme, which connects public authorities with startups developing circular infrastructure solutions enabling the integration of successful solutions into new tenders to scale up sustainable practices. Digital tools such as Building Information Modelling (BIM) and material passports further support digital twins of buildings and circular construction by enabling the tracking of material flows and reuse potential, and assessing future renovation needs (OECD, 2024b). The Netherlands participates in European sustainable procurement networks such as SPP Next, which connects public sector frontrunners to share insights, best practices, and strategies around sustainable procurement (Afval Circulair, n.d.). Through such collaborative networks and the Public Procurement Expertise Centre PIANOo, Dutch authorities and public procurement teams actively share innovative practices, including specifying functional units rather than particular products or service, and promote the integration of lifecycle thinking into public procurement processes (PIANOo, n.d.).

5 Conclusion

Public procurement plays a critical role in accelerating the transition toward a circular built environment by shaping market demand for sustainable construction solutions. European policy frameworks increasingly support this transition by encouraging lifecycle-based evaluation methods, circular design principles, and the integration of environmental and social criteria within procurement processes.

However, significant challenges remain in the practical implementation of lifecycle-based procurement approaches. Limited technical expertise, fragmented lifecycle data, and the complexity of sustainability assessment methods continue to constrain the widespread adoption of tools such as LCSA.

The Dutch experience demonstrates that innovative instruments such as the Environmental Cost Indicator, lifecycle databases, and digital technologies can effectively integrate sustainability criteria into procurement procedures while stimulating innovation within the construction sector.

Strengthening circular procurement across Europe will require further development of standardized lifecycle methodologies, improved data availability, and enhanced capacity-building for procurement professionals. Practical implementation could be further supported through harmonised digital material passports, mandatory lifecycle reporting requirements, and wider adoption of ECI-type evaluation tools. By combining regulatory frameworks, digital tools, and market incentives, public procurement can evolve into a powerful driver of systemic change toward a low-carbon, circular, and resilient built environment.

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Enabling Structural Steel Reuse: Pathways for an Italian Pre-demolition Audit

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Abstract. Pre-demolition audit plays a key role in enabling circular construction by identifying materials and components suitable for reuse. This function becomes particularly relevant for structural steel, whose durability and mechanical properties make it well suited for multiple life cycles. This study reviews Pre-Demolition Audit practices across European and international contexts, analysing them from the perspective of structural steel recovery and reuse. The analysis highlights that, despite strong national performance in circular economy indicators, Italy still lacks a structured Pre-Demolition Audit framework oriented towards structural reuse, with current practices largely focused on waste management. To address this gap, the paper proposes a conceptual pathway for a reuse-oriented Pre-Demolition Audit tailored to the Italian context. The framework integrates reconstruction of structural knowledge, reuse-oriented dismantling planning, post-removal verification and digital traceability tools such as Digital Product Passports. Such an approach can strengthen the role of Pre-Demolition Audits as an interface between demolition planning and performance-based structural reuse within circular construction systems.

Keywords: Pre-Demolition Audit · Circular Economy · Steel Reuse · Deconstruction · Component Recovery

1 Introduction

The transition towards circular models in the built environment has progressively shifted attention from end-of-life waste management towards strategies aimed at preserving the value of construction materials through reuse. Within this context, the PDA has evolved from a tool primarily focused on waste characterisation and hazardous material identification into an instrument that increasingly incorporates reuse potential assessment [1], particularly where selective dismantling and traceability mechanisms are in place. At the same time, the PDA should be understood as only one component within a broader process intended to enable the circulation of secondary products and to support the development of markets for recovered construction elements.

Structural steel represents a particularly relevant case within this transition. Its durability and retained mechanical properties make it technically suitable for reuse; however, structural reapplication requires reconstructing the technical profile of elements,

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anticipating verification procedures and establishing traceability, increasing the informational and methodological demands on the audit phase. In Italy, although recycling performance is well established [2], structured pathways for the reuse of load-bearing steel components remain limited and are not yet systematically embedded within PDA procedures.

This paper reviews international PDA practices from the perspective of structural steel recovery and proposes a sequenced pathway for a reuse-oriented audit framework tailored to the Italian context, repositioning the PDA as an interface between demolition planning, structural verification and the circulation of reusable components. Based on this analysis, a conceptual pathway for a reuse-oriented PDA adapted to the Italian context is proposed.

2 Pre-demolition Audit Practices

The regulatory and technical landscape surrounding PDAs encompasses a broad spectrum of European instruments, from waste management protocols to standardisation initiatives and research projects, with priorities shifting progressively from waste optimisation toward material recovery and component reuse. At EU level, the Construction and Demolition Waste Management Protocol [1] supports PDAs and reuse within the waste hierarchy [3], but does not establish a technical structure for qualifying reusable structural components. The EU Taxonomy Regulation [5] identifies the construction sector among the environmentally sustainable economic activities within its scope, and encourages selective dismantling and material valorisation, though without defining performance-based procedures for structural reuse. The Level(s) framework [4] similarly promotes material recovery without addressing structural qualification within the audit phase. A CEN TC 350/SC1 Technical Specification [6] on PDAs is expected to consolidate national practices and align audit procedures with emerging data requirements, though its treatment of structural qualification remains to be clarified. At the research level, PARADE [7] and CityLoops [8] have structured the audit process around documentary analysis, site inspection and inventory preparation, explicitly recognising reusable components. FCRBE [9, 10] introduced the Reclamation Audit concept, producing structured inventories of materials suitable for reclamation, including structural elements. PROGRESS [11] further linked audit activities to the technical validation of load-bearing steel components, connecting preliminary documentation review and confidence-based classification to subsequent verification procedures. Table 1 provides an overview of country-specific PDA instruments identified across European and selected international contexts, reflecting the heterogeneity of national regulatory approaches. The framework proposed in this paper integrates the audit phase with structural knowledge reconstruction, dismantling planning and digital traceability, positioning the PDA as an operational interface between demolition activities and performance-based structural reuse.

The instruments identified reflect heterogeneous approaches to pre-demolition assessment, varying in regulatory status, procedural scope and degree of integration of reuse objectives, as discussed below.

Pre-Demolition Assessment across the examined national contexts remains primarily oriented towards the separation of materials for recycling, while reuse is generally

Table 1. Overview of national Pre-Demolition Audit instruments across European and selected international contexts

Country/Context	Instrument	Mandatory	Action
Austria	ÖNORM B 3151 [12]	No	Selective dismantling
Belgium	Sloopopvolgingsplan [13] Tracimat [14]	Yes (Flanders)	Material separation
Denmark	EK nr. 496/2024 [15]	Yes	Material separation
France	PEMD diagnosis [16] digital platform [17]	Yes	Explicit reuse evaluation, market circulation
Germany	DIN SPEC 91484 [18] DIN SPEC 91525 [19]	No	Documentation, Post-Use Concept
UK	Demolition Protocols [20, 21] GLA guidance [22]	No	Material valorisation, project-specific reuse
USA	Guide to Deconstruction [23] Guide to Material Reuse [24]	No	Material recovery, landfill diversion

limited to components considered suitable for a second life cycle. Within this framework, Germany and France stand out for the sophistication of their regulatory approaches.

Germany has established a two-tier normative framework: DIN SPEC 91484 defines the documentation and reporting requirements for PDAs, ensuring a structured and traceable process, while DIN SPEC 91525 introduces the Post-Use Concept, requiring the identification of potential subsequent use pathways for construction products already during the audit phase, thereby anticipating reuse conditions before dismantling and supporting early recovery planning.

France has developed one of the most advanced regulatory model in this field. Since 2021, the PEMD diagnosis (Produits, Équipements, Matériaux et Déchets) has been mandatory for buildings exceeding 1,000 m^2 of floor area. It consists of a comprehensive inventory of all materials leaving the site, prioritising reuse and, where not feasible, recycling, in order to minimise waste generation. A dedicated digital platform, developed by the Centre Scientifique et Technique du Bâtiment and the Agence de la transition écologique, supports project owners in carrying out the diagnosis and reporting, making anticipated material flows visible before construction begins and enabling the early activation of recovery and valorisation channels.

Italy presents a distinctive case within this international landscape. The country has long required demolition waste to be processed with the aim of maximising recycling and, where possible, reuse, a principle further reinforced by D.M. 127/2024 [25]. Supporting instruments include UNI/PdR 75:2020 [26], which addresses Design for Disassembly, and the Minimum Environmental Criteria (CAM 2025) [27], which promote selective demolition and material recovery through the End-of-Life Plan. This document is produced at the design stage, is not mandatory, and functions as an award criterion in public procurement, making it one of the more proactive tools in the Italian framework. In some

respects, it shares conceptual ground with a Material Passport, though it does not reach the same level of component-specific detail. It also opens, to a limited extent, to the reuse of structural materials, but dedicated regulatory support for this practice remains absent, leaving the pathway underdeveloped in structural terms.

Across the diverse contexts examined, a common pattern emerges: while the PDA is widely established as a material inventory and waste management instrument, its systematic integration with structural qualification procedures, particularly for steel elements, remains uneven. This gap becomes central when shifting from recycling-oriented performance to high-value structural reuse strategies.

3 Structural Qualification in the Pre-demolition Audit

Structural steel makes visible the methodological shift required when a PDA is expected to support performance-based reuse rather than recycling-oriented recovery. Steel retains its mechanical properties over long service lives and is technically suited to reuse; however, structural reapplication requires more than material identification. It depends on reconstructing the technical profile of each element, including geometry, cross-section, connection configuration, fabrication logic and, where available, material grade and service history. In existing buildings, such information is often incomplete or fragmented, limiting certainty at the preliminary audit stage.

Recent normative developments clarify the required level of verification. CEN/TS 1090–201 [28], complementing EN 1090–2, defines requirements for identification, traceability, dimensional verification, condition assessment and inspection prior to structural reapplication. This effectively raises the informational threshold to be met during or immediately after the audit when structural reuse is envisaged. The audit thus becomes the first link in a chain leading to formal structural qualification, and where a Post-Use perspective is adopted, the future application of components must already be considered during assessment.

A further issue concerns the sequencing of evaluation and verification. During the audit, steel members remain in situ and assessment is largely visual and non-intrusive. Hidden corrosion, cross-sectional loss and residual capacity, particularly in connection zones, can only be fully assessed after dismantling and cleaning, making post-removal dimensional checks and, where necessary, non-destructive or mechanical testing an integral part of the reuse pathway. The distinction between direct reuse, reuse after refurbishment and reuse requiring re-engineering is therefore relevant in defining the scope and expected output of the audit.

These aspects indicate that the challenge lies not in merely including reuse within audit procedures, already present in several regulatory and research contexts, but in aligning audit outputs with performance-based structural qualification. In contexts where audit practices remain predominantly recycling-oriented, such as Italy, this alignment is not yet systematically embedded, and bridging this gap requires repositioning the PDA as a coordinated interface between structural knowledge reconstruction, dismantling strategy and verification processes.

Based on the analysis of international practices and emerging technical standards, a reuse-oriented PDA can be structured as a six-step process (see Fig. 1) aimed at

progressively reducing uncertainty regarding the reuse potential of structural steel elements.



Fig. 1. Pre-Demolition Audit structure.

4 Towards a Reuse-Oriented Pre-demolition Audit for Italy

A reuse-oriented PDA in Italy should extend existing selective demolition practices by integrating procedures consistent with performance-based structural qualification, transforming the audit from a descriptive inventory into a structured assessment capable of anticipating and enabling structural reuse.

Where available, the End-of-Life Plan serves as the starting point for the audit. he process should then proceed with the reconstruction of a structural knowledge baseline, structured according to CEN/TS 1090–201. The level and reliability of this baseline determine the admissible test protocol for each component and, consequently, its possible Post-Use condition, defining whether qualification may rely primarily on documentation or require additional testing.

Audit findings must then be integrated with dismantling planning. Removal strategies such as unbolting rather than cutting directly affect reuse feasibility, and the dismantling sequence must be aligned with the prefigured Post-Use pathway. Where reuse is intended off-site, Construction Consolidation Centres [29], can operate as specialised infrastructures for reception, temporary storage, preparation and preliminary technical assessment of reclaimed structural elements, supporting components whose documentation is incomplete towards formal qualification. At the same stage, the audit should identify the qualified parties capable of carrying out the necessary verification and reworking procedures, including certified testing laboratories, specialised dismantling contractors and consolidation centre operators, so that responsibilities are defined before dismantling begins and the qualification chain is established from the outset.

The history of the demolished building, the technical profile of individual components, and the results of inspections and tests should be preserved within a digital component passport, accessible online and stored in open-source, non-proprietary formats to ensure interoperability and traceability across projects and life cycles. The passport should also record logistical information, including dismantling procedures, transportation, storage conditions and ownership transfers, as well as data supporting structural assessments, economic evaluations and life cycle analyses. To strengthen the secondary market of reused steel, a digital notification system modelled on the French experience could be introduced, uploading structured audit data to a central platform and making available quantities visible to specialised operators. A similar system already exists in

Italy. Developed with the support of ENEA, SUN [30] was created with the aim of facilitating industrial symbiosis processes: what is considered waste material for one industry may become a valuable raw material for another.

Through this structured integration of knowledge reconstruction, Post-Use prefiguration, dismantling coordination and digital governance, the PDA can become a technical and organisational connection between demolition and structural requalification, allowing Italy to complement its strong recycling performance with credible pathways for structural reuse. The feedback loop embedded in the proposed process (see Fig. 2) from use back to knowledge reconstruction, reflects a broader implication: existing buildings in use are already potential repositories of qualified structural components.

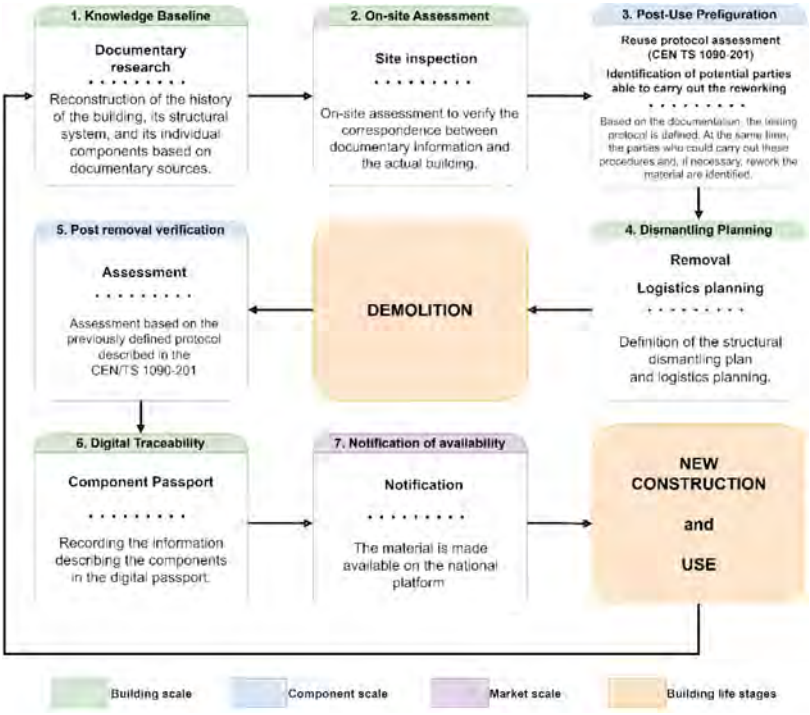


Fig. 2. The proposed process extends the conventional Pre-Demolition Audit beyond the demolition phase to encompass post-removal verification and digital governance.

Documenting and maintaining the technical profile of structures throughout their service life, rather than reconstructing it solely at the pre-demolition stage, would progressively constitute a structural material bank available to future reuse cycles, reinforcing the audit's role as a lifecycle instrument rather than an end-of-life one.

5 Conclusions

The review of European and international regulatory frameworks and research initiatives shows that current audit procedures are still predominantly oriented towards waste management and recycling, while systematic integration of structural reuse considerations remains limited. The proposed shift carries implications that extend beyond individual projects. When audit outputs are standardised, digitally accessible and linked to notification platforms, the PDA becomes an enabling infrastructure for industrial symbiosis. The flow of structural components from demolition sites towards receiving projects, consolidation centres and secondary markets begins to resemble the material exchange logic of mature circular industrial ecosystems. Demolition is no longer an endpoint but a sourcing phase, and the building stock becomes a material repository whose value is activated through structured knowledge and traceability.

For Italy, developing this capacity would mean not only closing a gap with more advanced European regulatory contexts, but also leveraging existing strengths in recycling and steel production to build credible pathways for high-value structural reuse. The approach integrates documentation analysis, on-site inspection, dismantling planning, post-removal verification and digital traceability mechanisms. The PDA, repositioned as the interface between demolition planning and structural requalification, is the instrument through which this transition can begin.

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Impediments to a Reduction of Embodied Carbon Emissions from Buildings, Underlying Reasons and Potential Solutions

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Abstract. The onset of climate change caused by anthropogenic greenhouse gas emissions has been well documented for decades. However, global annual emissions are still increasing, and the world is likely to exceed 1.5 °C global warming, at least temporarily. The construction of buildings has the potential to contribute to a significant reduction of these emissions because it is responsible for approximately 8% of global annual CO_2 emissions. Technical solutions for such a reduction have been available for years but their potential remains largely untapped. The reasons for this "implementation gap" are organisational rather than technical. In order to accelerate the necessary transformation of building construction in the near future, the prevailing impediments need to be better understood and resolved. The ultimate test of any carbon reduction strategy is clearly against a real-world building project. Therefore, real and live projects offer valuable opportunities to study frequently arising impediments, and to subsequently develop suitable strategies to resolve them. The major apparent impediments are low client ambition, undefined emission targets, and unsuitable procurement processes for design teams and contractors. Though all these impediments appear at the project level, some of them need to be addressed through different channels, e.g., legislation, policy framework and knowledge transfer. Based on the professional experience of the authors, expert interviews, and case studies, this paper covers critical impediments to the reduction of embodied carbon emissions in buildings, underlying reasons, and potential solutions in order to expedite the reduction of those embodied carbon emissions on a broader basis.

Keywords: buildings · sustainability · carbon emissions · decarbonisation · embodied carbon · barrier

1 Introduction

The onset of climate change caused by anthropogenic greenhouse gas emissions has been well documented for decades. Despite repeated appeals of climate scientists to urgently reduce greenhouse gas emissions, global annual greenhouse gas emissions

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are still increasing and the world is likely to exceed 1.5 °C global warming, at least temporarily.

In 2023 within the buildings sector, the construction, operation and maintenance of buildings accounted for 34% of global annual energy-related CO_2 emissions. This 34% can be further broken down into 8% resulting from construction and maintenance (embodied carbon) and 26% resulting from operation (operational carbon). The revised Energy Performance of Buildings Directive, which came into effect in the European Union in 2024, requires newly built public and private buildings to have a net zero operation as of 2028 and 2030 respectively. The emissions of new buildings in this instance would then be approximately 100% embodied carbon. However, only a few countries, including Denmark and France, have so far enacted mandatory regulations that prescribe limits of embodied carbon emissions from new buildings. This study focuses on the embodied carbon emissions from the structure of buildings, because it typically accounts for around 60 to 70% of the whole building's embodied carbon.

Technical solutions for a major reduction in embodied carbon emissions from building structures by around 50% have been readily available for years, but their potential remains largely untapped, at least on a broader basis. There is a large number of publications that provide technical design strategies to reduce embodied carbon emissions. Despite this, the general awareness for predominant show-stoppers to such reductions is comparably low and the number of related publications is rather limited so far. However, for a significant and successful reduction in embodied carbon emissions in buildings on a broader basis it is currently essential that prevailing impediments are better understood and resolved. Driven first by the obvious "implementation gap" between the availability of suitable technical solutions and their actual implementation in building projects, and second by the perceived "publication deficit", the authors tried to answer the following question: What are the critical impediments to a reduction of a building's embodied carbon emissions and how can they be resolved?

Barriers to the decarbonisation of buildings have been studied since around 2009, with a significant growth in the number of relevant publications as of 2015 [1, 2]. However, the majority of these publications focus on operational instead of embodied carbon emissions or sustainability in general [3, 4]. In addition, these studies typically do not aim at carving out the critical barriers that are directly responsible for the lack of carbon emissions reductions in real-world building projects. Instead, they often look at the bigger picture, establish comprehensive lists of barriers and allocate them to the various stakeholders of the built environment and other actors in society. Many, if not the majority, of the identified barriers are often far beyond the reach of building project stakeholders and can only be addressed in the long-term e.g. raising societal appreciation of sustainability. It also seems questionable, whether the resolution of such barriers would actually result in any real change. Although it would be ideal to resolve all these barriers, it simply seems to be overly time-consuming to implement a limit in global warming to 1.5 to 2.0 °C compared to pre-industrial levels in compliance with the Paris Agreement. Therefore, in this study we aim at identifying the minimum number of "critical impediments", which have a direct impact on real-world building projects and must inevitably be resolved to reduce their embodied carbon emissions. The authors did not find any study, that investigated the correlation between the barriers identified in the

study and the actual carbon rating of buildings. However, this is important in order to evaluate whether a barrier is in fact critical or not and therefore, such an investigation has been conducted as part of this study.

The ultimate test of any carbon reduction strategy is clearly against a real-world building project. They offer valuable opportunities to study frequently arising impediments and to develop suitable strategies to resolve them. During the course of building projects, it becomes quite clear which design options are typically favoured by project stakeholders, as well as the reasoning. Lessons learnt from such projects are essential to implement change and accelerate transformation. Therefore, this study is mainly based on knowledge gained from real-world projects.

2 Methods

In order to identify the impediments against the reduction of embodied carbon emissions from buildings, a three-step multi-method approach was pursued. The reason for this approach was to make sure that the results do not only reflect the opinions and professional experience of the authors but also that of a wider stakeholder group. The objectives also included the extent to which the impediments apply, quantification of the impact on the global warming potential (GWP), as well as the interdependencies between extent and impact, in real-world projects.

In the first step, the authors developed an initial hypothesis for frequently arising impediments at various project stages. This was based on a literature review as well as the authors' extensive professional experience and observations in the management, design, tender, and construction of real-world building projects, and their related advisory services background.

In the second step, the authors conducted a series of seven structured expert interviews using the funnel approach. Firstly, an open-ended question was asked about the impediments experienced by the experts in their own projects. Secondly, the initial hypothesis of the authors was tested through four further in depth questions, each related to a particular impediment. Finally, the experts were given the opportunity to mention any impediments, that had not been raised during the interview yet. All seven experts are from Bollinger + Grohmann and Arup and they were involved in key roles at least in the design and tender of various building projects.

In the third step, and based on the impediments identified in the two previous steps, the authors conducted case studies comprising 29 European building projects in Germany (14), Austria (7), France (4), Hungary (2), Belgium (1), and Italy (1), in which Bollinger + Grohmann provided structural engineering services during all design and tender stages. Each project included a comprehensive GWP life cycle assessment for their building structure including life cycle modules A1 to A3, C3 and C4. These particular projects were selected based on a consistent GWP dataset and accurate bills of quantities derived from fully finalised construction drawings. Firstly, each project was evaluated against whether and which of the previously identified impediments were predominant, and to what extent. Afterwards, the results in terms of predominant impediments and GWP-ratings were combined and compared in order to identify any correlations and trends.

Though this study focuses on the structure of buildings, its findings are likely applicable to other building elements, e.g., façade and fit-out as well. A limitation of this study regarding the correlation between impediments and GWP-ratings is probably the relative small sample of projects included in the study.

3 Impediments

3.1 Identified Impediments

The following four critical impediments were identified in this study.

Low Client Ambition (IMP1). This impediment summarises all issues related to a lack of or low client ambition to reduce embodied carbon emissions. This includes inconsistencies between the client's ambition expressed at the beginning of a project, and their actual decision-making process in later project stages when the client's priorities might change. If this impediment prevails, all the other impediments are very likely to occur as well. In this study, this impediment does not cover any sustainability ambitions other than the reduction of carbon emissions, e.g., not including circularity indicators.

Undefined Emission Target (IMP2). This impediment summarises all issues related to the absence of a clear and measurable definition of an emission target, e.g., a max. GWP of 250 $kgCO_2eq./m^2$ including life cycle modules A1 to A3, C3, and C4 for the structure of the building. When this impediment occurs, all subsequent processes in the project, including procurement, design option evaluation, and decision-making, are very likely also not aligned with the client's ambition. This means that at project completion, it will probably not be clear whether the client's ambition has been achieved or not. In this study, this impediment does not cover any sustainability targets other than GWP, e.g., not including the amount of reused or recycled materials.

Unsuitable Design Team Procurement Process (IMP3). This impediment summarises all issues related to a design team procurement process, in which tender documents do not include a clear and measurable requirement specification that all bidding design teams need to fulfil. Such a specification is a prerequisite for a proper bid evaluation and comparison. This impediment also covers a missing emission target (mandatory or linked to financial incentives) in the design contract, similar to the agreement of a maximum construction cost or a time schedule. If this impediment applies, the client is usually unable to assess and compare the capabilities of the bidding design teams and to ensure that their emission target is met after contract award and during the design stage. A poor design or poorly specified design will usually significantly reduce the contractor's potential to meet the client's emission target.

Unsuitable Contractor Procurement Process (IMP4). This impediment summarises all issues related to a contractors procurement process in which tender documents do not include a clear and measurable requirement specification that all bidding contractors need to fulfil. Such a specification is a prerequisite for a proper bid evaluation and comparison. This impediment also covers missing emission limits for key building materials, e.g., concrete, reinforcement, and steel, and for the construction process, including transport to the site in the construction contract, similar to the agreement of a maximum construction

cost or a time schedule. If this impediment occurs, the client is usually unable to assess and compare the capabilities of the bidding contractors and it is difficult to ensure that their emission target is met after contract award and during the construction stage.

3.2 Significance and Nature of the Impediments

The findings of the case studies are summarised in Table 1.

All four impediments were observed with a very high frequency which indicates their high relevance. In 45% of the projects all four impediments were fully observed; in 72% at least three; in 86% at least two; and in 90% at least one of these impediments applied. In 97% of the projects all four impediments were fully or partially observed, and in 100% at least three of the impediments applied. IMP1 fully applied to 48% of projects, IMP2 to 90%, IMP3 to 83%, and IMP4 to 72%.

The case study did not show a strict correlation between the number of impediments prevailing in a project and its embodied carbon rating. However, the probability for a relatively poor carbon rating increased significantly when all four impediments fully applied. All four impediments did not fully apply to any of the top-rated six projects, they only fully applied in 17% of the top-twelve projects, but in 65% of the bottom 17 projects.

The four impediments typically occur in a similar distribution, as mentioned above, across the various project stages. Therefore, each impediment can individually act as a final show-stopper, no matter how well the other impediments are resolved.

All four impediments are organisational rather than technical in their nature, which is in alignment with the findings of other studies [4]. This means they cannot be addressed by the improvement of existing technical solutions or the development of new technical solutions.

Certain project conditions can have a positive impact on the carbon rating despite a predominance of impediments. If a client decides to refurbish an existing building or to use a timber structure, which might not even be driven by his desire to reduce carbon emissions, the carbon rating would typically be improved, e.g., project #7. If a design team or a design and build contractor "voluntarily" delivers a building with a low carbon rating at no or minimum extra cost and time, which might be driven by their desire to showcase their expertise, the carbon rating would also be improved.

Table 1. Summary of the case studies' findings

Project ID	GWP [kgCO_2eq./m^2]	Structural Material	IMP1	IMP2	IMP3	IMP4
#1	140	T/C	+	–	–	–
#2	147	T/C	o	–	–	–
#3	153	T/C	o	–	–	–
#4	158	C	o	o	o	o
#5	159	T	o	–	–	–

(*continued*)

Table 1. (*continued*)

Project ID	GWP [kgCO_2eq./m^2]	Structural Material	IMP1	IMP2	IMP3	IMP4
#6	159	C	o	–	o	o
#7	163	T	–	–	–	–
#8	166	S/C	o	–	–	–
#9	172	C	o	o	o	o
#10	181	T	o	–	–	–
#11	184	C	–	–	–	–
#12	199	C	o	–	–	–
#13	217	C	–	–	–	–
#14	232	C	–	–	–	–
#15	233	C	o	–	–	o
#16	235	S/C	–	–	–	–
#17	237	T/C	o	–	–	o
#18	238	C	–	–	o	–
#19	249	T	–	–	–	–
#20	256	S/C	–	–	–	–
#21	257	C	o	–	–	o
#22	260	C	–	–	–	–
#23	262	C	o	–	–	o
#24	277	C	–	–	–	–
#25	326	T/C	–	–	–	–
#26	341	C	o	o	o	o
#27	365	C	–	–	–	–
#28	401	C	–	–	–	–
#29	653	C	–	–	–	–

The following abbreviations were used in the table above: T Timber, S Steel, C Reinforced Concrete, + Impediment does not apply, o Impediment partially applies, – Impediment fully applies

4 Underlying Reasons and Potential Solutions

It is important to understand the underlying reasons for the identified impediments in order to develop potential solutions to resolve them. However, reasons and solutions are closely related, and are therefore discussed here in combined subchapters. Subsequent references to "client" also apply to other project stakeholders but the client's role is essential to resolve the impediments.

4.1 Low Client Ambition

The major reasons for this impediment are clients' priority for cost and time over sustainability, and their risk aversion and distrust related to processes and technical solutions that deviate from conventional methods. Other key reasons include the lack of experience clients have to set up and manage projects in a way that facilitates ambitious emission targets, and a lack of awareness concerning existing technologies to reduce embodied carbon emissions in buildings. Additional reasons are the low appreciation of clients concerning the impact of climate change, the importance of tackling it, and the significant potential of building construction to reduce embodied carbon emissions as a whole. The reasons identified here are in good alignment with the results of other studies, though most of them only address a subset of the reasons elaborated above [1–4].

At a policy level, independent of any one project, this impediment can and needs to be resolved by the introduction of legal regulations and financial incentives that prescribe the consideration of environmental costs and allowable limits to embodied carbon emissions in buildings. At project level and at the very beginning of a project, this impediment can be resolved by raising the awareness of the associated benefits of low emission buildings to clients, e.g., a future-fit building and a lower risk that the buildings become stranded assets in the near future. Another part of the solution is advising clients on a reliable and goal oriented project setup, on the advantages, challenges and cost implications of innovative technologies, and increasing the awareness of clients concerning the urgency of climate action and their potential role at the very beginning of a project, and well before the procurement of any other project participants.

4.2 Undefined Emission Target

This impediment is primarily caused by clients' limited awareness of the importance of clearly defined and measurable emission targets in reducing embodied carbon emissions, alongside a knowledge gap concerning long-term carbon investment and the establishment of realistic, achievable targets. Some other studies address the reasons identified here in similar detail [4] but most of them on a more general level, e.g. lack of understanding, goals and data [1, 2].

At knowledge transfer level and independent of any one project, this impediment can be resolved by improving the public data availability of GWP-evaluations for buildings from completed projects, based on fully finalised construction documentation, with transparent quantity setup and GWP-data, e.g., by making life cycle assessments using controlled GWP-data mandatory for building permit applications and requiring regular publishing of results. The introduction of legal regulations and financial incentives mentioned in the previous subchapter can resolve this impediment as well. At project level and at the very beginning of a project, this impediment can be resolved by advising clients on the importance of a clearly defined emission target, on future-fit but realistic target values, and on their potential cost impact.

4.3 Unsuitable Design Team and Contractor Procurement Processes

The key reasons for this impediment are low client experience relating to the entire construction value chain and proper specifications of embodied carbon reduction objectives

(mandatory or linked to financial incentives), and the associated obligations of the design team / contractor to be included in the tender and contract documents. Other reasons are low awareness of clients concerning the importance of procurement processes in achieving an ambitious emission target, and in selecting capable design teams and contractors for this task. Some other studies address these reasons in similar clarity [4] but most of them on a more general level, e.g. lack of knowledge [1, 2].

At knowledge transfer level, independent of any one project, and at project level at the very beginning of a project, well before the procurement of any other project participants, this impediment can be resolved by advising clients on the complexity and fragmentation of the construction value chain and on suitable tender and contract specifications [5]. Another part of the solution is to increase the awareness of clients on the challenges related to identifying and selecting capable design teams and contractors in the current state of market readiness. Tender specifications should clearly state the requirement for design teams /contractors to present precedence projects where certain GWP-levels were met, and a method statement outlining how they intend to meet the client's emission target. Tender specifications for contractors should require them to submit evidence, e.g., environmental product declarations, that materials assumed in their bids are suitable to meet the client's emission target.

5 Conclusion

The four impediments identified are highly relevant and frequently apply in building projects. Their resolution is currently critical to expedite the reduction of embodied carbon emissions from buildings on a broader basis. Legal regulations and financial incentives are central among the proposed solutions.

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Measuring Sustainable and Circular Urban Development Through Eurostat SDG Indicators: Evidence from Four European Countries

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Abstract. This study examines how sustainability and circularity principles contribute to reshaping the built environment in Europe, using Eurostat's Sustainable Development Goals (SDG) indicators as the primary analytical source. The objective is to evaluate how circular practices support regional development and reduce spatial disparities in four cohesion policy–driven countries: Poland, Romania, Portugal, and Italy.

The methodology employs quantitative regression analysis using indicators for SDG 9 (Industry, Innovation and Infrastructure), SDG 10 (Reduced Inequalities), and SDG 11 (Sustainable Cities and Communities) obtained from the Eurostat Sustainable Development Goals database for the period 2015–2024. Using NUTS-2 regional data from Poland, Romania, Portugal, and Italy, the study examines how innovation capacity and inequality influence sustainability outcomes across regions. A complementary policy discussion evaluates the role of European Union cohesion and circular economy strategies in supporting sustainable urban development.

Preliminary results show that while all four countries exhibit progress toward sustainability and circularity, significant regional disparities persist. Regions with stronger innovation capacity and greater access to green services exhibit better SDG alignment, whereas structurally disadvantaged areas experience slower transitions despite policy interventions.

The study highlights how harmonised SDG data can guide more inclusive, circular, and future-oriented strategies for transforming the built environment, offering practical insights for policymakers and planners.

Keywords: Circular Economy · SDGs · Regional Development · Built Environment

1 Introduction

Sustainable urban development and the circular economy transition have gained increasing prominence in academic and policy contexts. EU cities are key spatial units where economic growth, environmental sustainability, and social well-being intersect. This

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study examines how regional innovation capacity and socioeconomic inequality jointly influence sustainability outcomes at the NUTS-2 level, asking: (1) how does innovation capacity shape circular urban development? (2) to what extent do regional inequalities constrain sustainability performance? and (3) do regions with stronger innovation and lower inequality achieve better sustainability outcomes?

Furthermore, the study provides a comparative analysis, highlighting significant differences in sustainable and circular urban development across NUTS-2 regions in Poland, Romania, Portugal and Italy. In doing so, the study aims to provide a comprehensive assessment of the multidimensional nature of sustainable urban development, accounting for regional disparities across Europe. The remainder of the paper is structured as follows: Sect. 2 presents the literature review; Sect. 3 describes the dataset and methodology; Sect. 4 reports the empirical findings; and Sect. 5 discusses the results and provides overall conclusions.

Although previous studies have examined sustainable urban development, circular economy transitions, innovation systems, and regional inequalities separately, limited research has comprehensively analysed the interactions among SDG 9, SDG 10, and SDG 11 at the NUTS-2 level. This study addresses this gap by providing a comparative regional analysis across Poland, Romania, Portugal, and Italy using harmonised Eurostat SDG indicators, advancing understanding of regional sustainability transitions and circular urban development in Europe.

2 Literature Review

The SDGs provide a comprehensive framework linking economic development, environmental sustainability, and social inclusion. SDG 9 (Industry, Innovation and Infrastructure), SDG 10 (Reduced Inequalities), and SDG 11 (Sustainable Cities and Communities) are particularly central to sustainable and circular urban systems (1, 2). The circular economy is a fundamental element of this transformation. It aims to reduce the environmental impact of economic systems by reusing resources in production and consumption processes and by closing loops through recycling and material reuse (3).

Regions with high innovation capacity advance sustainable urban development more rapidly, as regional innovation systems foster collaboration among universities, industry, and government to develop circular urban solutions (4). Circular economy policies also depend on technological and institutional innovations that improve resource efficiency and strengthen waste management systems (5). Circular economy policies also depend on technological and institutional innovations that improve resource efficiency, promote sustainable production, and strengthen waste management systems (6). Smart city technologies and digital infrastructures further strengthen sustainable urban systems (7) (8). The built environment is one of the most significant domains where circular economy principles can be operationalised through sustainable construction practices, resource-efficient infrastructure, urban regeneration, and resilient urban planning. Within the SDG framework, these dimensions are reflected in indicators of innovation capacity, infrastructure quality, urban sustainability, and regional inequality.

The goal of reducing inequalities, as addressed under SDG 10, is directly related to social inclusion, access to services, and quality of life in cities (1). Regional inequalities

can be decisive for access to infrastructure investments, economic opportunities, and the distribution of environmental resources (9).

European evidence confirms that economically disadvantaged regions underperform on key sustainability indicators, including transportation infrastructure, housing quality, and access to green spaces (10). This also hampers circular economy implementation, as resource-constrained regions struggle to undertake sustainable infrastructure investments (2).

The circular economy requires not only technological but also socioeconomic restructuring (11). In regions with high innovation but also high inequality, sustainability policies may have limited inclusive effects; conversely, low inequality with weak innovation may slow circular economy adoption. Balanced socio-economic conditions and strong innovation ecosystems are therefore jointly necessary for sustainable urban transitions (12). These factors are driven by economic growth, innovation capacity, and institutional frameworks (13). It is especially noted that regions in Southern and Eastern Europe face greater structural challenges in meeting sustainable urban development goals (14).

3 Data and Methodology

This study explores the relationship between innovation capacity, inequality, and sustainability outcomes using Eurostat SDG database indicators (2015–2024), which provide harmonised measures of SDG progress across European regions. The dataset includes indicators on innovation capacity (SDG9), inequality (SDG10), and urban sustainability outcomes (SDG11). Composite indices for SDG9 and SDG10 were constructed using z-score standardised indicators aggregated via arithmetic mean, a widely used and transparent approach in sustainability research (15, 16). Prior to aggregation, each indicator was standardised using z-score normalisation (subtracting the mean and dividing by the standard deviation) to ensure comparability across regions and countries with different measurement scales. The arithmetic mean of the standardised indicators was then computed to construct each composite index. This approach is transparent and widely used in sustainability indicator studies. The SDG9 index captures regional innovation capacity and infrastructure development, while the SDG10 index reflects socioeconomic inequality conditions within regions..

Poland, Romania, Portugal, and Italy were selected as they represent diverse economic structures, innovation capacities, and inequality patterns within the EU, and have all benefited significantly from EU structural funds while continuing to face regional disparities. Innovation capacity (SDG9) was assessed using three indicators: R&D expenditure (SDG9_10), high-technology exports (SDG9_40), and employment in high-technology sectors (SDG9_50). The SDG9 composite index was calculated as the arithmetic mean of these standardised indicators.

$$sdg9_{indexi} = (sdg9_{10i} + sdg9_{30i} + sdg9_{50i})/3 \quad (1)$$

where (SDG9_INDEX_i) represents the innovation capacity for observation (i). Inequality performance (SDG10) was similarly measured using three indicators—SDG10_10, SDG10_30, and SDG10_50—reflecting different aspects of income distribution and

socioeconomic inequality. The SDG10 composite index was computed as the arithmetic mean of these standardised indicators.

$$sdg10_{indexi} = (sdg10_{10i} + sdg10_{30i} + sdg10_{50i})/3 \quad (2)$$

where higher SDG10_INDEX values indicate stronger progress in reducing inequalities.

The dependent variable, HighLowSustain, was constructed by dichotomising the continuous SDG11 indicator at its mean value (8.79): regions at or above the mean were classified as high-sustainability performers (value = 1), and those below as low-sustainability performers (value = 0). While this binary transformation facilitates interpretation and comparative analysis, it simplifies the continuous nature of the underlying sustainability construct.

To test whether inequality moderates the effect of innovation capacity on sustainability outcomes, an interaction term was created as the product of the SDG9 and SDG10 indices. The empirical model is specified as follows:

$$HLS_i = \beta_0 + \beta_1 sdg9_{index_i} + \beta_2 sdg10index_i + \beta_3 sdg9index_i \backslash sdg10_{index_i} + \in_i \quad (3)$$

where HLS is the binary sustainability outcome, SDG9_INDEX and SDG10_INDEX are the composite innovation and inequality indices, their product captures the moderation effect, β_0 is the intercept, β_1–β_3 are regression coefficients, and ($\in\varepsilon$_i) is the error term.

Although the dependent variable is binary, Ordinary Least Squares (OLS) regression was employed as an exploratory analytical approach given its interpretability for identifying broad linear associations. The model was checked for heteroskedasticity using the Breusch-Pagan test; where detected, robust standard errors were applied. Multicollinearity was assessed via variance inflation factors (VIF). As a robustness check, a logistic regression specification was also estimated and produced qualitatively consistent results. Nonetheless, the OLS findings should be interpreted cautiously given the binary nature of the dependent variable, and future studies are encouraged to apply more advanced econometric approaches.

4 Results and Discussion

A multiple linear regression was estimated to examine the relationships among innovation capacity (SDG9), inequality (SDG10), and sustainability outcomes (HighLowSustain), including an interaction term to test for moderation effects. The constant is statistically significant (B = 2.010, p = 0.003), indicating a positive baseline sustainability level when both indices are held at zero.

As displayed in Table 1, the coefficient for the SDG9 Index is negative and statistically insignificant (B = −0.001, p = 0.601), indicating that variations in regional innovation capacity do not significantly influence sustainability outcomes in the analysed dataset. This result suggests that higher levels of innovation capacity alone are not associated with meaningful changes in sustainability performance across the examined regions. Although the standardised coefficient for SDG9 is relatively large in magnitude (Beta = −0.672), the lack of statistical significance suggests that this relationship may be driven by sample characteristics or multicollinearity with the interaction term, rather than a genuine effect.

Table 1. Result of the Regression Model of the Study

Variable	B	Std. Error	Beta	t-value	p-value
Constant	2.010	0.604	–	3.327	0.003
SDG9 Index	−0.001	0.001	−0.672	−0.530	0.601
SDG10 Index	0.000	0.000	−0.688	−2.501	0.020*
SDG9 × SDG10	6.17E-08	0.000	0.810	0.601	0.554

Source: Author's own calculation (2026)
Notes: $p < 0.05$*

In contrast, the SDG10 Index is statistically significant ($p = 0.020$). The negative standardised coefficient (Beta $= -0.688$) indicates that higher inequality is associated with lower sustainability outcomes, suggesting that regions with greater socioeconomic disparities face greater challenges in achieving SDG targets.

To further investigate whether inequality moderates the relationship between innovation capacity and sustainability outcomes, an interaction term between SDG9 and SDG10 indices (SDG9 × SDG10) was added to the regression model. However, the results show that this interaction effect is not statistically significant (B = 6.17E−08, $p = 0.554$). This suggests that the impact of innovation capacity on sustainability outcomes does not vary significantly across regions with different inequality levels. In other words, inequality does not appear to moderate the link between innovation capacity and sustainability performance within this sample.

The country-level disaggregation reveals distinct sustainability profiles. Poland shows moderate SDG11 performance, with better outcomes in innovation-intensive NUTS-2 regions (e.g., Mazowieckie) compared to peripheral areas, reflecting uneven cohesion fund absorption. Romania exhibits the weakest sustainability scores, consistent with its higher SDG10 inequality values and pronounced urban–rural divides. Portugal achieves comparatively stronger sustainability outcomes, particularly in Lisbon and Norte regions, driven by digital transformation and green infrastructure investments. Italy displays the starkest internal disparities: northern regions (e.g., Lombardia, Emilia-Romagna) significantly outperform southern regions (e.g., Calabria, Sicilia) across all SDG dimensions, reflecting deep structural differences in industrial capacity and institutional quality. Across all four countries, regions with lower SDG10 inequality scores tend to record higher SDG11 sustainability outcomes, reinforcing the regression findings.

Across all four countries, reducing regional inequalities appears to play a more decisive role in improving sustainability outcomes than innovation capacity alone.

5 Conclusion

This study examined the roles of innovation capacity (SDG9) and inequality (SDG10) in shaping sustainability outcomes (SDG11) across NUTS-2 regions in Poland, Romania, Portugal, and Italy. The results show that innovation capacity has no statistically significant direct effect on sustainability performance, suggesting its impact may be indirect or

context-dependent. In contrast, inequality emerges as a significant negative determinant: higher socioeconomic disparity is associated with lower sustainability, highlighting the critical importance of inclusive development. The non-significant interaction term indicates that these two dimensions operate largely independently within the model. These findings carry important policy implications: EU cohesion and circular economy strategies should combine innovation-oriented investments with targeted inequality-reduction measures, as technology adoption alone appears insufficient to drive sustainable urban transitions without concurrent social cohesion efforts.

Despite its contributions, this study has several limitations. The analysis covers only four European countries, the binary transformation of the sustainability variable simplifies complex dynamics, and the study relies on secondary Eurostat indicators. Future research should employ longitudinal or panel data, include additional control variables, and apply logistic regression or other nonlinear techniques to improve robustness. Exploring alternative moderating mechanisms—such as governance quality or digital transformation would further advance understanding of the pathways linking innovation, inequality, and sustainable development.

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Digital and Circular Policy Alignment for a Zero-Waste Construction Sector

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Abstract. This study examines the international regulatory and strategic landscape driving the twin transition—digital and circular—within the construction sector, with a specific focus on the management and valorisation of Construction and Demolition Waste (CDW). The analysis concentrates on the regulatory frameworks of the European Union (EU), the United Kingdom, and China, highlighting how policies and standards seek to address data fragmentation and the uneven level of digital maturity across the sector.

The study assesses alignment with key EU policy instruments, including the European Green Deal, the Circular Economy Action Plan (CEAP), the proposed Construction Products Regulation (CPR), and the Digital Product Passport (DPP). It also explores the integration of technical standards such as BIM EN ISO 19650 and EN ISO 20887 for Design for Disassembly. In parallel, strategic initiatives in the United Kingdom and China are examined, notably the Build Back Greener strategy and the 14th Five-Year Plan for the Development of the Circular Economy.

The findings identify common opportunities related to the adoption of digital technologies for material traceability and selective deconstruction. Overall, the global regulatory framework is increasingly oriented towards mandatory life cycle data (LCA) and digital transparency, establishing a strategic foundation to accelerate the transition towards a zero-waste construction sector by 2050.

Keywords: Digital construction · Circular economy · CDW management · Life Cycle assessment · BIM standards · International regulation

1 Introduction

The Construction sector is one of the most resource-intensive industries globally, accounting for over 30% of global resource extraction and generating between 30% and 40% of the world's solid waste, commonly referred to as Construction and Demolition Waste (CDW) [1]. To mitigate these profound environmental impacts, the industry is undergoing a "twin transition" – a strategic alignment of digital transformation with the shift towards a circular economy (CE) [2, 3].

Despite the acknowledged benefits of this transition, the global implementation of circular practices faces an important barrier: the fragmentation of data and an uneven level of digital maturity across the supply chain [2]. The lack of centralized data repositories and poor interoperability hinder the tracking of materials and the assessment of their

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reusability. This study examines how international regulatory frameworks -specifically in the European Union (EU), the United Kingdom (UK), and China- are seeking to address these data fragmentation challenges, establishing the strategic and technological foundations to accelerate the transition towards a zero-waste construction sector by 2050 [2, 4, 5].

2 Methodology and Analytical Framework

This study combines a comparative policy review with a multi-level theoretical framework to analyze the Twin Transition (digital and circular) in the construction sector. The analysis draws upon a structured review of recent peer-reviewed literature and key strategic policy instruments from the European Union (EU), the United Kingdom (UK), and China, focusing on digitalization and Construction and Demolition Waste (CDW) management.

To systematically evaluate the interplay between regulatory evolution and technological adoption, the study adopts the Digital Circularity Alignment Model (DCAM), recently conceptualized by Lindblad (2026) [6]. Although originally developed through a systematic review of timber construction, the DCAM provides a theoretically transferable analytical lens for broader building contexts. The model avoids technological determinism by integrating the Resource-Based View (RBV) with sociotechnical transitions theory, decomposing systemic complexity into four interdependent layers:

- Digital Infrastructure: Foundational tools enabling data traceability (e.g., BIM, Digital Product Passports).
- Circular Strategies: Operational practices (e.g., Design for Disassembly, selective deconstruction).
- Business Models: Economic structures institutionalizing circularity (e.g., Product-as-a-Service).
- Institutional Context: Public policies, procurement frameworks, and regulatory mandates.

Model Adaptation. In this study, the DCAM is adapted as a macro-level analytical lens to examine how the evolution of the Institutional Context (Layer 4) in the EU, the UK, and China shapes the deployment of Digital Infrastructure (Layer 1). The analysis focuses on how regulatory mechanisms condition the digital prerequisites necessary to overcome supply chain data fragmentation and operationalize CDW valorization.

3 International Regulatory and Strategic Landscape

The adoption of circular economy principles is increasingly driven by policy frameworks that mandate greater transparency and resource efficiency.

3.1 The European Union (EU)

The EU is spearheading global regulation through the European Green Deal, which aims for climate neutrality by 2050 [1, 2]. Within this framework, the Circular Economy

Action Plan (CEAP) identifies construction as a priority, resource-intensive value chain [1, 2]. A cornerstone of this strategy is the recently updated Construction Products Regulation (CPR – Regulation EU 2024/3110), which harmonizes rules for the marketing of construction products and promotes circularity [7, 8]. Its most transformative element is the mandatory introduction of the Digital Product Passport (DPP), a structured digital record that stores essential data regarding a product's origin, composition, environmental impact, and recyclability capabilities [2, 8].

3.2 The United Kingdom (UK)

The UK has adopted a strategy heavily focused on waste reduction and carbon management. The government is introducing a Circular Economy Strategy that targets construction as a priority sector to slash waste and strengthen supply chains [9, 10]. Furthermore, strategic initiatives like the Construction Playbook mandate the early-stage assessment of whole-life value and carbon in public procurement [10, 11]. Local policies, such as the London Plan, also enforce mandatory Whole Life-Cycle Carbon (WLC) assessments and Circular Economy Statements for major developments [10, 12].

3.3 China

China is addressing the circular transition through high-level macroeconomic directives. The 14th Five-Year Plan for the Development of the Circular Economy (2021–2025) establishes ambitious numerical targets, aiming to increase resource productivity by 20% and promoting the massive reuse of solid and construction waste [5]. These national strategies are operationalized through pilot programs like the "Zero Waste City" initiative in Schenzen, which mandates source reduction of CDW through green building standards and the extensive use of prefabricated buildings [13].

4 Integration of Technical Standards: BIM, ISO 19650, AND ISO 20887

To overcome information fragmentation, regulatory frameworks increasingly rely on international standards that homogenize digital and construction processes.

4.1 BIM and ISO 19650 Series

Building Information Modelling (BIM) is the central digital enabler for design and data management [2, 3]. The adoption of the BS EN ISO 19650 series is critical, as it provides a globally recognized framework for managing information throughout project's lifecycle, from the delivery phase to the operational phase [11]. This standard ensures that data flows seamlessly across a Common Data Environment (CDE), facilitating global compatibility and collaboration.

4.2 Design for Disassembly (DfD) and ISO 20887

For materials to circulate effectively, buildings must be conceived as material banks [14]. The standardization of Design for Disassembly principles (e.g., ISO 20887) ensures that building components can be separated and recovered without damage at the end of their useful life [14, 15]. Integrating DfD principles within BIM models allows architects to anticipate future material recovery pathways, reducing the need for virgin resources [14].

5 Material Traceability, Life Cycle Assessment (LCA), and Selective Deconstruction

The successful valorisation of CDW relies heavily on the availability of empirical data and adequate deconstruction practices.

5.1 Digital Transparency and Material Passports

The Digital Product Passport (DPP) interacts directly with BIM models and Digital Building Logbooks (DBL) [2]. By assigning unique identifiers (such as GS1/GTIN standards) to physical products, DPPs ensure end-to-end material traceability [2, 8]. This transparency allows stakeholders to verify the presence of hazardous substances and assess recycling potential decades after a product's installation [3].

5.2 Selective Deconstruction

As an alternative to traditional demolition, selective deconstruction guarantees the safe removal of hazardous materials (e.g., asbestos) and improves source separation for high-quality recycling [16]. Supported by mandatory pre-demolition audits, this practice radically increases the purity and value of recovered fractions like concrete, metals, and timber [16].

5.3 Mandatory Life Cycle Assessment (LCA)

Globally, regulations are moving towards mandatory life cycle data collection. For instance, the revised EU Energy Performance of Buildings Directive (EPBD) requires the progressive calculation and reporting of whole-life carbon (WLC) emissions for all new buildings by 2028 and 2030 [12]. Integrating LCA tools with BIM enables designers to optimize material choices and reduce embodied carbon from the earliest stages of a project [10, 12].

6 Comparative Analysis and Results: Convergences, Structural Differences, and Emerging Opportunities

The comparative analysis of the European Union (EU), the United Kingdom (UK), and China reveals both convergences and structural differences in the regulatory approaches driving the twin digital and circular transition in the construction sector. Across the three regions, policy frameworks increasingly integrate digital infrastructures such as Building Information Modelling (BIM), Digital Product Passports (DPPs), and Life Cycle Assessment (LCA) to enhance material traceability, resource efficiency, and Construction and Demolition Waste (CDW) valorization [1, 2]. However, governance models and implementation pathways differ significantly.

Table 1 synthesizes the principal convergences and divergences identified across the three jurisdictions.

Table 1. Comparative overview of regulatory approaches to the twin transition in construction

Dimension	EU	UK	China
Governance approach	Supranational regulation	Procurement-driven governance	State-led planning
Key instruments	Green Deal, CEAP, CPR, DPP	Construction Playbook, Circular Economy Strategy	14th Five-Year Plan, Zero Waste City
Digital infrastructure	BIM, DPP, DBL	BIM, WLC tools	Smart construction, prefabrication
CDW strategy	Traceability, DfD	Waste and carbon reduction	Reuse and prefabrication
Main challenge	Interoperability	Fragmented implementation	Regional disparities
Opportunities	Secondary material markets	Circular procurement	Digital monitoring and AI

Despite these differences, all three regions show a clear shift toward higher-value circular strategies, including selective deconstruction, reuse, and life-cycle-based planning [14, 16]. Digital technologies are increasingly positioned as enabling infrastructures for regulatory compliance rather than optional innovation tools.

Key persistent barriers include data fragmentation, interoperability limitations, and uneven digital maturity across stakeholders [2, 5]. These challenges suggest that achieving a zero-waste construction sector by 2050 will depend not only on technological development, but also on the alignment between regulatory frameworks, digital infrastructures, and implementation capacity.

7 Discussion

The comparative analysis reveals a clear global convergence towards integrating digital tools as regulatory compliance mechanisms for circularity in the construction sector. However, the findings also highlight a structural misalignment between regulatory ambition and operational readiness across the supply chain.

7.1 Regulatory Convergence vs. Implementation Capacity

Across the EU, the UK, and China, regulatory frameworks increasingly mandate life cycle transparency, material traceability, and waste valorisation. Nevertheless, the ability of industry actors -particularly SMEs- to operationalize these requirements remains uneven. While supernational instruments such as the EU's Digital Product Passport create standardized expectations, their effective deployment depends on digital infrastructure maturity and interoperability standards at firm level [2, 18].

This gap suggest that policy harmonization alone is insufficient; implementation capacity becomes a critical enabling factor [5, 12].

7.2 Interoperability as a Systemic Bottleneck

A current issue identified across all regions is data fragmentation. The regulatory push for traceability (DPPs, BIM mandates, LCA reporting) presupposes seamless data exchange across actors and life cycle phases [1, 2]. However, proprietary software environments and inconsistent data schemas limit the integration of material-level information into project-level decision-making [5].

The findings indicate that interoperability standards (e.g., open BIM formats and harmonized ontologies) are not merely technical add-ons but structural prerequisites for regulatory effectiveness [5].

7.3 Governance Models and Transition Pathways

The comparative analysis reveals three distinct governance mechanisms:

- The EU adopts a harmonized legislative approach based on binding supranational regulation [1, 19].
- The UK leverages public procurement and market instruments [11].
- China operates through macroeconomic planning and large-scale pilot programs [5].

Despite their structural differences, all three approaches rely increasingly on digital infrastructure as an enforcement mechanism. This suggests that digitalization is evolving from a voluntary innovation tool to a regulatory backbone within circular transition strategies.

7.4 Implications for the Twin Transition

The findings confirm that digitalization alone does not automatically produce circularity. Instead, circular outcomes emerge when digital infrastructure, regulatory mandates, and business incentives are aligned [1, 5]. The DCAM framework demonstrates analytical value in identifying these interdependencies and highlighting where misalignments persist.

Achieving a zero-waste construction sector by 2050 will therefore depend not only on technological advancement but on coordinated governance strategies that integrate digital standards, economic incentives, and mandatory life cycle accountability.

8 Conclusions

This study analyzed how regulatory and strategic frameworks in the European Union (EU), the United Kingdom (UK), and China are shaping the twin digital and circular transition in the construction sector, with particular attention to Construction and Demolition Waste (CDW) management. The comparative review shows a growing convergence toward policies that promote life-cycle transparency, material traceability, and digitalization as key enablers of circular construction practices.

Despite differences in governance approaches—supranational regulation in the EU, market- and procurement-driven strategies in the UK, and state-led planning in China—all three regions increasingly rely on digital infrastructures such as Building Information Modelling (BIM), Digital Product Passports (DPPs), and life-cycle assessment (LCA) frameworks to support resource efficiency and waste valorization.

The application of the Digital Circularity Alignment Model (DCAM) highlights the importance of aligning regulatory mandates with digital infrastructures to address persistent challenges such as data fragmentation and uneven digital maturity across the sector. These findings suggest that advancing toward a zero-waste construction sector will depend not only on technological innovation but also on coordinated regulatory frameworks that enable interoperable data ecosystems and effective implementation across the supply chain.

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Comparative Assessment of the Construction and Demolition Waste Policy Instruments in Estonia and Latvia

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Abstract. Construction and demolition waste (CDW) represent the second largest industrial waste stream in Estonia after the oil shale industry, accounting for nearly 17.5% of all waste generated in 2021. While Estonia aims to comply with the EU's circular economy requirement to prepare 70% of CDW for reuse, recycling, and recovery, the current CDW management performance still has substantial unrealized potential, particularly in relation to systemic demolition with subsequent material reuse, high-quality recycling, and the development of secondary material markets. Using data from environmental institutions, national legislative documents, and statistical databases, this study reviews Estonia's CDW management current status. The analysis is complemented by a comparative assessment of Estonia's status relative to selected neighbouring country – Latvia. The observed challenges include limited implementation of selective demolition, uneven sorting capacity across regions, nascent demand for secondary materials, and limited economic initiatives — that challenge circular practices in construction. Addressing these barriers, the paper analyzes development pathways aimed at enhancing circularity and improving CDW management across the sector, including facilitating high-quality mineral recycling and expanding digitalization opportunities for CDW management. The study synthesizes the aforementioned findings and provides a comprehensive analysis of the Estonian CDW market and gives evidence-based recommendations to support Estonia's transition toward a circular and resource-efficient construction sector.

Keywords: Construction and Demolition Waste · Circular Economy · Waste Management · Market Development · Recycled Materials

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1 Introduction

The construction sector drives economic growth but imposes major environmental burdens through resource extraction, land use, greenhouse gas emissions, and substantial waste generation at end-of-life [1]. Construction and demolition waste (CDW), comprising concrete, bricks, metals, wood, gypsum, plastics, excavated soils, and more, is one of the largest and most complex waste streams worldwide and in the European Union (EU) [2].

Growing material demand and shorter building lifespans intensify pressure to reduce material intensity and environmental impact. Poor CDW management results in excessive landfilling, resource inefficiency, and setbacks to climate neutrality and circular economy objectives. The EU Waste Framework Directive (2008/98/EC) mandated at least 70% recovery, reuse, or recycling of non-hazardous CDW by 2020, yet high-quality material circularity remains elusive [3].

Challenges stem from treating CDW primarily as "waste" rather than a resource, which discourages investment and innovation. Urban planning seldom incorporates resource efficiency or reuse requirements, while fragmented EU-wide regulations hinder standardization and cross-border trade in secondary materials. Planning prioritizes functionality and cost over circular design and renovation [1].

Technological constraints, inefficient sorting, lack of standardized processing, and limited high-value separation infrastructure, further restrict viable recovery [1]. These are exacerbated by weak economic incentives and enforcement, making landfilling or low-grade recovery the norm. Achieving circularity demands clear definitions, technical advances, robust market signals for secondary materials, and digital enablers such as material passports, tracking tools, and pre-demolition audits [4]. Stakeholders, from regulators and authorities to contractors, developers, and waste managers, play pivotal roles in advancing or impeding circular practices.

This paper assesses CDW management in Estonia and Latvia using a qualitative three-dimensional framework (legislative effectiveness, economic incentives for reuse, and infrastructural readiness). Based on systematic review of policy documents, scientific literature, and comparative analysis, the paper identifies practical levers to enhance material circularity in both countries' construction sectors.

2 Overview of Policy Instruments for CDW Management

Policy instruments promoting CDW circularity are categorized in various ways by type (e.g., economic, regulatory, informational) or mechanism (direct vs. market-based) [5]. This paper applies a functional classification across legislative, economic, and infrastructure dimensions, enabling detailed analysis of their impact on CDW collection, processing, and reuse [2].

Legal mandates are essential for CDW governance. National laws, circular economy strategies, and CDW provisions in construction regulations form the regulatory core [6]. Countries like Japan and the Netherlands have improved recycling outcomes through strict waste laws and selective demolition rules [11]. Strategies increasingly emphasize CDW reuse and recovery [12], while integrating selective demolition and waste separation in Building Codes to support circularity [6].

Financial instruments also shape CDW recovery [6]. Key tools include subsidies, landfill taxes, Green Public Procurement (GPP) preferences, and enforcement penalties [8]. Landfill taxes, effective in Denmark, the Netherlands, and the UK, have halved CDW landfilling [11]. GPP requirements drive market demand, and penalties ensure compliance with recovery targets [8].

Infrastructure underpins CDW management [2], including regional recycling facilities, digital traceability tools, material banks, and on-site separation [24]. Processing centers reduce landfill use, though infrastructure gaps remain in many developing contexts [12]. Building Information Modeling (BIM) enhances traceability and reuse [10], while material banks and selective demolition support efficient recovery [14].

3 Methodology

To assess the policy landscape and examine the current state of CDW management in Estonia and Latvia, the study employs a qualitative, multi-dimensional assessment framework. The research design is grounded in a systematic review of academic literature, national policy documents, institutional reports, and statistical data. The analytical framework comprises three core dimensions, i.e. legislative, economic, and infrastructural, each operationalized through a set of eleven policy instruments that capture regulatory performance, economic incentives and disincentives, and the availability of technical and organizational infrastructure supporting CDW circularity. These instruments span CDW-related laws and regulations, national strategies, financial mechanisms such as subsidies and landfill taxes, public procurement requirements, enforcement measures, as well as key infrastructural components including sorting and recycling capacity, digital traceability tools, material banks, and on-site separation or selective demolition practices.

Each policy instrument was evaluated using a structured qualitative approach, combining a 3-point Likert scale (present, not present and no data) at both national and municipal levels. The strength of each instrument was determined based on three criteria: policy clarity, degree of implementation, and institutional maturity. These assessments were informed by evidence drawn from legal frameworks, national strategy documents, and municipal regulations. The literature review used a systematic search of peer-reviewed publications (2019–2025), focusing on CDW recycling, economic drivers, policy implementation, and barriers to circular construction. Sources included ScienceDirect, publisher portals, and open-access PDF repositories. This was complemented by analysis of national frameworks and official reports to ensure comprehensive institutional coverage.

A comparative analysis examined the CDW management in Estonia and Latvia across the three dimensions, analyzing regulatory approaches, circularity practices, and infrastructure maturity. This mixed-methods approach enabled identification of critical gaps, overlaps, and bottlenecks, providing an evidence base for targeted recommendations aligned with EU circular economy goals.

4 Results and Discussion

4.1 National Framework for CDW Management in Estonia

Estonia's CDW management is governed by national laws, EU directives, and municipal regulations. The Waste Act [23], aligned with the EU Waste Framework Directive, mandates separate collection of major waste fractions but lacks requirements for pre-demolition audits or CDW reuse. The Building Code allows recovered materials if standards are met [26], though it does not directly address circular design or waste minimization obligations.

The National Waste Plan 2023–2028 [18] targets a 10% CDW reduction and 40% reuse/recycling (excluding backfilling) by 2028. Selective demolition is recommended but not mandated. Local authorities oversee CDW collection; for example, Tallinn requires on-site sorting of key fractions [14], while smaller municipalities show inconsistent enforcement. A 2024 Environment Agency report attributes low separation rates and low landfill costs [13].

Municipalities apply waste rules guided by national plans [16], with some financial incentives. The main economic tools are landfill tax (€0.63/t) and pollution fees (~€50–55/t) [16]. Local initiatives, like the Estonian Recycling Competence Centre, promote recycled materials and have supported projects like a recycled road base [13]. Estonia reports high recovery rates (approximately 90% in recent years), yet most is low-value backfilling or aggregate reuse. According to national data, 32% of CDW was recycled in 2020, rising slightly to 39% in 2021. Going forward, Estonian and Latvian CDW recovery initiatives intend to progress toward high-quality circular practices [13].

CDW is processed at around 531 sites, mostly in Tallinn, with 13 municipalities lacking facilities. Costs vary based on waste type, handler, and logistics. Municipal ordinances define CDW handling obligations [13]. Digital tools like BIM and material passports remain in early use. Material banks exist in major cities but lack national coordination. Selective demolition and on-site separation are encouraged locally but not legally required. Contractors cite low incentives, limited awareness, and space constraints as main barriers [13].

4.2 National Framework for CDW Management in Latvia

Latvia's CDW management is shaped by national laws, strategic plans, and EU-aligned initiatives. The Waste Management Law [21] defines roles for CDW producers and sets requirements for collection, sorting, and treatment. The State Waste Plan 2021–2028 sets national targets in line with EU directives. A key development is the LIFE Waste to Resources project [25], which introduced 2024 CDW guidelines developed by government, industry, and municipal actors. These standardize on-site separation practices for demolition and construction. Municipalities such as Riga enforce binding CDW handling and documentation rules aligned with national policy [25].

Despite reforms, circular practices remain less attractive than landfilling due to weak incentives and low secondary material demand. Reuse is undervalued, and recycling is regulation-driven rather than market-led. Rising landfill taxes have improved economics

[24], but secondary materials still struggle to compete with low-cost virgin aggregates especially in remote regions where transport adds cost [25].

Infrastructure includes national sorting facilities, recycling plants (e.g., for concrete, bricks), landfills, export channels (especially for metals), and emerging valorization initiatives. However, capacity is concentrated in Riga, which hosts most high-tech facilities. Rural areas rely on small sorting centers and landfills, limiting material recovery and reinforcing regional disparities [25].

4.3 Comparison of Situations in Estonia and Latvia

Table 1. Cross-comparison of CDW management in Estonia and Latvia

Dimensions	Instruments	Estonia NL	Estonia ML	Estonia N/A	Latvia NL	Latvia ML	Latvia N/A	Observations
Legislation	Laws and regulations for CDW	■			■			Both countries share similar challenges in selective demolition.
	Circular economy strategy for CDW	■	■		■	■		
	CDW management and selective demolition in Building Code	▨			▨			
Economic	Subsidies for the reuse of CDW in construction projects			▩			▩	Latvia's economic policy supports circularity; Estonia's framework permits recovery such as backfilling.
	Landfill tax on CDW	■	■		■	■		
	Public procurement requirements for the use of secondary construction materials	▨			▨		▩	
	Penalties for non-compliance with CDW separation/reuse targets			▩			▩	
Infrastructure	Availability of CDW sorting and recycling facilities per region		■			■		Latvia invests strategically in CDW infrastructure, but enforcement is a challenge; Estonia's framework is clear and compatible with digital solutions.
	Digital tools for CDW traceability (e.g., BIM, material passports)			▩			▩	
	Availability of material banks for reuse of CDW	▨	■				▩	
	On-site separation capacity and selective demolition practices	▨	■			▨		

Note: ■ Present, ▨ Not present, ▩ No data

NL – National level, ML – Municipal level, N/A – Not available

Both Estonia and Latvia operate under EU waste legislation, yet their CDW systems differ notably in legislative strength, economic drivers, and infrastructure. Neither

country mandates selective demolition, but Latvia's economic measures (higher landfill taxes and Natural Resource Tax) and infrastructural initiatives (especially the LIFE Waste-to-Resources project) provide a strong overall push toward circularity, improving on-site sorting, recycling capacity, and early secondary material market development. Estonia also is active and has a relevant project LIFE IP BuildEST. Estonia has formalized reporting structures and data obligations but economic incentives permit low-value recovery in addition to high-quality material loops. Enforcement also varies: Estonia shows regional variations, with stronger guidance in Tallinn and larger cities. Latvia maintains uniform national permitting yet still faces compliance gaps. Infrastructure profiles differ: Estonia records high overall recovery rates but depends on low-value backfilling. Latvia has pursued targeted investments through recent programmes.

Both countries share similar challenges in selective demolition, high-value recycling capacity, and secondary materials markets. Harmonized Baltic regulations, joint standards, and procurement policies to drive demand for recycled content could collectively accelerate regional circularity in construction. The mapped results are presented in Table 1.

5 Conclusion

Estonia and Latvia are advancing circular economy principles in construction sector, yet key gaps persist. Estonia has a clear policy framework conducive to digital solutions but relies on low-value recovery like backfilling. Latvia shows strong economic and infrastructure progress, supported by higher landfill taxes and CDW initiatives, but still seeks to enhance secondary material use. Both countries share similar challenges in selective demolition, high-value recycling capacity, and secondary materials markets. Both Estonia and Latvia recognize CDW's strategic role in national waste plans and are investing in digital tools. In overall, achieving a resource-efficient construction sector in Estonia and Latvia requires organized legislation, financial incentives, and infrastructure development. By addressing these barriers, both countries have high potential to enhance CDW circularity and contribute to broader sustainability goals.

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Circular Economy KPIs in the Construction Sector: A Cross-Country Comparative Analysis

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Abstract. This paper presents a comparative analysis of circular economy (CE) key performance indicators (KPIs) in the construction sector across five countries: Greece, Portugal, Romania, Spain, and Türkiye. The study aims to identify common patterns and country-specific differences in the way circularity is measured and prioritised in national construction-related policy frameworks. To ensure comparability, KPIs were mapped onto a standardised framework based on the Ellen MacArthur Foundation's Circular Building Design Toolkit, covering four domains: Build Nothing, Build for Long-Term Value, Build Efficiently, and Build with the Right Materials. The results show a strong cross-country concentration of KPIs in the materials domain, while demand-reduction and building-stock optimisation strategies remain weakly represented. A second layer of analysis, based on KPI quality weighting, reveals significant differences in regulatory maturity, especially in the balance between monitoring indicators, compliance obligations, and binding quantitative targets. The study highlights key convergence patterns and structural gaps, supporting future harmonisation of CE measurement in construction.

Keywords: Circular economy · key performance indicators · comparative analysis · sustainability · construction sector

1 Introduction

The construction sector is central to the circular economy (CE) transition due to its high material consumption, waste generation, and contribution to energy use and greenhouse gas emissions [1]. CE offers an alternative to the linear model by keeping materials in use, minimising waste, and regenerating natural systems [2, 3]. In construction, this implies reducing resource use through reuse and recycling and designing buildings for longer life and adaptability [4]. To operationalise these principles in the built environment, measurable indicators are needed. Key performance indicators (KPIs) translate broad

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circularity objectives into comparable metrics that can support monitoring, evaluation, and decision-making in both policy and practice [4]. However, in Europe, CE-related indicators are often defined at a broad strategic level, for example in national circular economy action plans [2], and are not always tailored to the construction sector. Even where sector-specific KPIs exist, countries adopt different scopes, definitions, and measurement approaches, which limits benchmarking and cross-country learning. This paper addresses that gap by comparing construction-related CE KPIs across Greece, Portugal, Romania, Spain, and Türkiye using a common framework based on the Ellen MacArthur Foundation's Circular Building Design Toolkit [3].

2 Methodology

This study applies a comparative policy analysis to examine how CE is operationalised in the construction sector across Greece, Portugal, Romania, Spain, and Türkiye. The countries were selected to ensure regulatory and contextual diversity, including EU and non-EU systems, different market sizes, and varied territorial conditions. This heterogeneity supports the identification of broader structural patterns rather than country-specific effects. To ensure comparability, a standardised analytical framework was developed based on the *Circular Building Design Toolkit* proposed by the Ellen MacArthur Foundation (EMF). Construction-related KPIs identified in national legislation, policy documents, strategies, and sectoral regulations were mapped onto four CE domains: *Build Nothing* (refuse unnecessary new construction), *Build for Long-Term Value* (increase building utilisation; design for adaptability, longevity, and disassembly), *Build Efficiently* (refuse unnecessary components; increase material efficiency), and *Build with the Right Materials* (reduce the use of virgin materials; reduce the use of carbon-intensive materials; design out hazardous/pollutant materials).

National documents were selected through a targeted review of official legal, strategic, and regulatory sources. Only documents containing construction-related CE provisions with measurable indicators, targets, reporting duties, or enforceable obligations were included. For each country, KPIs were extracted and documented by name, definition, measurement unit, level of implementation, and policy source. The dataset was then organised into a comparative matrix. To assess the relative importance of each domain within national frameworks, the share of KPIs per domain was calculated. Equation (1) defines domain share:

$$Domain\ Share = \frac{KPIs\ in\ domain}{Total\ KPIs\ in\ country} \tag{1}$$

A second analytical layer assessed regulatory maturity by classifying each KPI into one of five quality-weighting categories: (1) Binding Quantitative Target (legally enforceable numerical target with a defined compliance threshold and timeline), (2) Compliance Obligation (mandatory procedural or operational requirement without a quantified performance target), (3) Economic Instrument (financial mechanism influencing behaviour (e.g., taxes, incentives)), (4) Monitoring Indicator (measurable performance metric used for tracking progress but lacking enforcement mechanisms), and (5) Technical Enabling Requirement (standard, specification, or regulatory provision that

enables circularity but does not mandate performance outcomes). This made it possible to compare not only what is measured, but also the degree to which circularity is embedded in regulation.

The method has some limitations. National KPIs differ in scope, legal force, and measurement logic, so comparison requires interpretative harmonisation. In addition, the presence of a KPI in legislation does not necessarily indicate implementation effectiveness or data reliability.

3 Comparative Results

Table 1 presents the normalised KPI families used for the domain-based aggregation in Table 2 and Table 3. Here, "normalised" refers to terminology harmonisation: nationally specific indicators with equivalent measurement intent were grouped under common KPI families.

Table 2 reports the KPIs relative distribution across the four EMF strategic domains within each national framework. Overall, the results show a clear cross-country convergence: circularity in construction is predominantly operationalised through the *Build with the Right Materials* domain. This domain accounts for the largest share of KPIs in all five countries, ranging from 58.33% in Greece to 84.62% in Spain, and includes indicators related to recycled content, secondary raw materials, embodied carbon, and hazardous material management. This pattern suggests that current national frameworks still approach circular construction mainly through material substitution and waste-derived inputs rather than through systemic transformation of building demand and use.

In contrast, *Build Nothing* is weakly represented in all five countries, indicating that avoidance of unnecessary new construction remains marginal in current KPI architectures. The *Build Efficiently* domain is also limited, although Portugal shows a comparatively stronger orientation toward process efficiency (18.75%) than the other countries. In Greece, no KPI was classified under this domain, pointing to a relative lack of indicators focused on material efficiency during construction and demolition processes.

The greatest cross-country variation appears in *Build for Long-Term Value*. Greece allocates 37.50% of its KPIs to this domain, substantially more than Türkiye (18.75%), Romania (13.33%), Spain (7.69%), and Portugal (0%). This indicates a stronger Greek emphasis on lifecycle performance, longevity, and adaptability, whereas Portugal and Spain remain far more concentrated in material-related indicators. Romania also shows a strongly material-centred profile, while Türkiye occupies an intermediate position, combining material-oriented metrics with a modest representation of long-term value indicators.

Table 3 complements this domain-based comparison by classifying KPIs according to their regulatory strength. The results reveal substantial differences in regulatory maturity. Greece and Spain display the highest shares of binding quantitative targets (29.17% and 23.08%, respectively), suggesting a comparatively stronger use of enforceable outcome-based instruments. Portugal and Romania rely more heavily on monitoring indicators and compliance obligations, indicating a more procedural and reporting-oriented approach. Türkiye is the clearest example of a monitoring-based framework, with 87.50% of its KPIs falling into this category and no economic instruments or binding quantitative

Table 1. Harmonised KPI families used as the basis for cross-country domain mapping

KPI	Gr	Pt	Ro	Es	Tr
Estimated quantity of construction and demolition waste (CDW) to be produced (by type) [5, 7]		✓		✓	
Fraction of CDW to be recycled or otherwise recovered [5, 7, 8]	✓	✓		✓	
Fraction of CDW to be eliminated (landfilled) [5, 9, 10]		✓	✓		✓
Reuse of materials in the work or in other destinations [5, 9, 11, 13]	✓	✓	✓		✓
Incorporation of recycled CDW in the work [5, 12]	✓	✓			
Selective collection and sorting coverage on-site [5, 6, 13, 14]	✓	✓	✓	✓	
Application of sorting methodology or transfer to licensed operator [5]		✓			
National CDW material-recovery rate [5, 15] [14–16]	✓	✓	✓	✓	✓
Minimum recycled-materials content in public works [17]		✓			
Recycled aggregates content (for Pt-in concrete) [17, 18]	✓	✓			
Recycled aggregates content in unbound pavement layers [17]		✓			
Use of CDW materials in embankments, landfill covers, rural roads and trench backfill [17]		✓			
Inert vs. hazardous fractions of CDW [6, 19, 20]		✓		✓	✓
Regional CDW generation and recovery rate [21]		✓			
Renovated building floor area [22]		✓			
Share of national waste that is CDW [17]		✓			
Certified Management Compliance [12]	✓				
Use of recycled aggregates [8, 9, 18]	✓		✓	✓	
CDW Prevention Target [18]	✓				
Use of the ‘Level(s)’ Framework [7]	✓				
Secondary Material Content in Constr. Products [7, 9, 16, 23]	✓		✓	✓	✓
Digital Enablement for Circularity (BIM, digital passports) [7, 14, 23, 33]	✓		✓	✓	✓
Most Economically Advantg. Tender - Circularity Weight [24]	✓				
Environmental Clause Compliance [24]	✓				
Life-Cycle Costing (LCC) Integration [24]	✓				
Use of Ecolabels in Technical Specifications [24]	✓				
Technical Specifications for Recycled Content [24]	✓				
Embodied Carbon Footprint (Life Cycle GHG) [25] [23]	✓			✓	
Primary Raw Material Reduction (Recycled Content) [26]	✓				
Design for Disassembly and Adaptability [26]	✓				

(*continued*)

Table 1. (*continued*)

KPI	Gr	Pt	Ro	Es	Tr
Life Cycle Assessment (LCA) Coverage [23, 26, 27, 33]	✓		✓	✓	✓
Electronic Building Identity Compliance [28]	✓				
Adaptive Reuse Ratio [23, 28]	✓				✓
Circular material use rate (CMU) [9, 11]			✓		✓
Renovation with circular materials [9]			✓		
Landfilling of Recoverable CDW (Hierarchy Compliance) [14]			✓		
Sustainable Use of Natural Resources [27]			✓		✓
Durability and Life-Cycle Performance [27]			✓	✓	
Recovery and Recycling Objectives Compliance [6]				✓	
Asbestos census and removal [29]				✓	
Recovered railway properties [15]				✓	
Preparation for reuse and recycling of CDW [15]				✓	
Waste valorisation rate [15]				✓	
Valorisation of CDW in port landfills [15]				✓	
Sustainable materials in stations [15]				✓	
Installation / Placement Waste [23]				✓	
Packaging Waste [23]				✓	
Primary energy consumption [23]				✓	
Use of locally sourced and recycled mat. in railway stations [23]				✓	
Recycling rate of CDW [32]				✓	
BIM Methodology for LCA [32]				✓	
Ecodesign in building projects [29]				✓	
On-site Sorting of CDW [9, 13]	✓		✓		
Selective Demolition Implementation [14, 29]			✓	✓	
Construction Waste Reduction Rate [30]					✓
Installation of used parts [20]					✓
Amount of Waste Generated [11]					✓
Wastewater Recovery Rate [11]					✓
Wastewater Reuse Rate [31]					✓
Design for Waste Prevention Index [33]					✓
Total	24	16	15	26	16

Note: Some KPI families are sector-wide or project-specific proxies for construction circularity and differ in scope and legal force across countries.

Table 2. Share of KPIs per Domain (%) for each country

Share of KPIs / Domain (%)	Greece	Portugal	Romania	Spain	Türkiye
Build Nothing	4.16%	6.25%	0.00%	3.85%	6.25%
Build for Long-Term Value	37.50%	0.00%	13.33%	7.69%	18.75%
Build Efficiently	0.00%	18.75%	6.67%	3.85%	6.25%
Build with the Right Materials	58.33%	75.00%	80.00%	84.62%	68.75%
Total	24	16	15	26	16

Table 3. Quality Weighting of KPIs for each country

Quality Weighting	Greece	Portugal	Romania	Spain	Türkiye
Monitoring indicator	16.67%	37.50%	40.00%	50.00%	87.50%
Compliance obligation	29.17%	25.00%	40.00%	15.38%	0.00%
Economic instrument	4.17%	0.00%	0.00%	0.00%	0.00%
Binding quantitative target	29.17%	18.75%	13.33%	23.08%	0.00%
Technical enabling requirement	20.83%	18.75%	6.67%	11.54%	12.50%

targets identified in the dataset. Taken together, these findings suggest that although the five countries converge around a material-centric understanding of circularity, they differ substantially in the balance between monitoring, compliance, and enforceable policy instruments.

4 Discussions, Recommendations and Limitations

The results suggest that construction circularity governance remains predominantly material-oriented. This reflects the regulatory origin of most KPIs: where indicators derive mainly from waste and material-recovery policies, they naturally focus on recycled content, CDW recovery, sorting, and hazardous-material control. Conversely, Build Nothing and Build for Long-Term Value depend more on planning, renovation, procurement, life-cycle assessment, and building-stock management, which are often regulated outside CE or waste frameworks.

Based on these findings, four priorities are proposed: harmonised core KPI families with flexible national sub-indicators; standardised reporting rules to address differences in terminology, calculation logic, and reporting levels; stronger links between monitoring-oriented KPIs and implementation mechanisms such as procurement, permitting, or binding targets; and better integration of adaptive reuse, renovation, lifecycle performance, and design-for-disassembly indicators.

Several limitations should be acknowledged. First, the analysis relies on officially documented KPIs and legislative provisions; informal practices, pilot initiatives, and

non-codified market mechanisms were excluded unless reflected in measurable indicators. Second, KPI mapping necessarily involved interpretative judgement, although a structured classification protocol was used to improve transparency and replicability. Third, some indicators could not be fully aligned with the EMF domains because they addressed broader governance functions, macro-level sustainability objectives, or policy inputs rather than construction-specific circularity outcomes. Finally, differences in terminology, calculation methods, reporting frequency, and legal structure limit strict cross-country comparability. These constraints underline the need for more harmonised and outcome-oriented CE KPI frameworks in the construction sector.

5 Conclusions

This study developed and applied a comparative framework for analysing CE KPIs in the construction sector across Greece, Portugal, Romania, Spain, and Türkiye. The results show that current KPI frameworks are strongly concentrated in material-related dimensions of circularity, while demand reduction and long-term value strategies remain comparatively weak. The quality-weighting analysis also highlights uneven regulatory maturity, particularly in the balance between monitoring indicators, compliance obligations, and binding targets.

Overall, the paper shows that a standardised, domain-based KPI framework can support cross-country learning while exposing gaps in comparability, data granularity, and policy balance. It offers a basis for harmonising CE measurement and supporting more balanced, lifecycle-oriented construction policy.

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Governance Policy Barriers and Opportunities for Material Reuse in Municipal Building Construction

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Abstract. The shift from a linear to a circular economy (CE) in the built environment has recently attracted significant attention. While research highlights opportunities such as urban mining, material banks, and LCA, their practical application in the public sector remains difficult. This paper explores how local municipal regulations, tools, and guidance documents restrict or support material reuse in municipal projects. The methodology comprises a systematic review of relevant regulations and guidance documents, complemented by interviews and observations in a chosen municipality. Many municipal documents and regulations aim to promote sustainability, but often unintentionally hinder reuse due to strict technical and regulatory requirements and guidance. The findings highlight the important role of regulatory frameworks in guiding CE practices in municipal construction. Misalignment between sustainability goals and operational needs creates barriers that restrict reuse potential, even when internal strategies aim to promote CE. By identifying these gaps and emphasising opportunities for improvement, the study offers practical insights to support reuse in public sector projects.

Keywords: Circular economy · Municipality · Policy · Governance · Built Environment

1 Introduction

The built environment (BE) accounts for most raw material extraction and greenhouse gas emissions [1, 2]. Furthermore, the sector generates nearly one billion tonnes of construction and demolition waste in the European Union (EU) alone [3]. In addition, studies indicate that demand for material resources in the BE will continue to rise, necessitating effective measures [4]. Adopting circular economy (CE) principles has significant potential to reduce greenhouse gas emissions in the BE [5], and studies show that material reuse is the most recommended solution for increasing resource efficiency [3, 6].

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There is a need for both national and municipal strategies to support the implementation of measures related to climate, environmental sustainability, and circularity [7]. The EU has been a strong driver of CE, with two action plans published in 2015 and 2020, which have influenced national, regional, and municipal strategies for implementing CE measures across Europe. A wide range of overarching goals and initiatives concerning circularity have already been introduced in public strategies, and several Nordic and Norwegian municipalities have begun to emphasise such measures [8, 9]. Nonetheless, there is considerable variation in how these goals are articulated and how municipalities work toward them.

Municipalities hold a unique role in the BE, acting as developers, owners, maintainers, and operators of buildings. This gives them a significant influence in promoting circular practices.

Furthermore, municipalities follow various local requirements, guidelines, tools, and procedures in rehabilitation, transformation, and new construction, which may unintentionally hinder circularity goals. This study examines a Norwegian municipality's strategies, goals, guidelines, and processes to identify how they support or hinder efforts. It also evaluates necessary adjustments to improve procedures and align them with local and national aims to increase circularity.

Therefore, the following research questions are posed:

RQ1: How do governmental policies hinder or facilitate the implementation of reuse practices in the municipal building sector?
RQ2: How can current municipal building processes be adapted to meet national and local circularity goals?

The study is limited to one of Norway's largest municipalities by population, focusing on reusing construction materials in municipal building projects.

2 Methods

2.1 Research Design

This study uses a qualitative case study approach, as described by Yin R. K [10]., to explore how municipal strategies, construction processes, and guidelines influence the municipality's efforts to implement circularity in its building projects. This choice aimed to thoroughly investigate a single municipality through interviews, document analysis, and observation. The case is set in the municipal property sector and is relevant to municipal building construction.

This study explores the reuse of construction materials in municipal construction, including materials recovered from existing structures, planning for reuse, and their application in new-build, refurbishment, and rehabilitation projects. The scope excludes recycling or reusing of crushed raw materials. Regarding the nine Rs of CE, reuse is defined here as medium loop and extending the life of materials [11]. In this context, construction materials refer to products such as concrete elements, timber, stone, steel, brick, and other fixed building components.

The research design integrates three complementary data sources: municipal documents and digital project tools, unstructured interviews with key stakeholders, and

observations. The document review offers an understanding of the formal governance structure, while interviews and observations provide insights into practices and decision-making processes. These documents help establish the formal institutional context of the case, and their inclusion enables cross-verification and a deeper understanding of the governance structures that shape municipal construction processes.

2.2 Data Collection and Analysis

The data material includes municipal climate strategies and action plans, project framework documents, technical specifications, internal guidelines, and descriptions in digital systems. The documents were selected based on observations conducted during the municipality's project activities, as well as unstructured informal interviews with relevant stakeholders involved in municipal construction processes [12]. The selected documents are therefore directly related to the municipality's building operations, ranging from initial requests submitted by property management to the execution of small and large construction projects. All documents and digital tools included in the study are relevant because they shape, guide, or influence the potential implementation of circular measures throughout the municipal project process.

Semi-structured interviews were conducted with municipal in-house consultants responsible for building, environmental, and CE, along with observations during project meetings and workshops (N = 7). Since the municipality only manages its own public buildings, the study focuses solely on municipal construction projects. The municipality is a mid-sized Norwegian municipality (~150,000 inhabitants).

To analyse the data collected in the study, the documents were reviewed and the digital tools examined to identify relevant formulations, decision points, and descriptions that might either support or hinder the implementation of circular measures in the design and planning processes. Interviews and observations were used to identify relevant aspects of the documents and to define the analytical focus areas. These focus areas, derived from the research questions, served as the principle for sorting and examining the material. The documents were organised according to these analytical focus areas.

The empirical material was analysed using qualitative content analysis [13], supported by thematic categorisation [14]. The analytical focus areas were developed deductively from the research questions and refined through insights from interviews and observations. These focus areas subsequently functioned as the organising structure for reviewing and categorising all data.

All relevant data were systematically read through, focusing on the interviewees' points regarding key aspects of the documents and processes. During the review, relevant formulations and sentences expressing guidelines on circular principles and reuse were identified.

3 Results

3.1 Framework for Managing Project Activities

The municipality carries out a wide range of projects, from small and large rehabilitation projects to new construction. The processes described in the municipal project framework, from the initial pre-analysis to the final decision point, are shown in Table 1.

Various tasks must be completed and assessed across all project types. Several phases, therefore, influence the implementation of reuse, and many actors and resources are involved throughout the process.

Table 1. Phases of the municipality's building project process, with description and owner.

Phase/Decision point	Description	Owner
Pre-analysis	Assess the need and determine whether further investigation is warranted.	Service Units
Decision point 1 (BP1)	Decide whether the identified need or project idea should be further developed in the concept phase.	Property Management
Concept phase	Establish a mandate, develop the project, assess needs, recommend a concept, and evaluate the phase.	Property Management
Decision point 2 (BP2)	Approve the chosen concept and decide on the start of the planning phase.	Property Management
Planning phase	Conduct a kick-off meeting, prepare preliminary project documentation, management documents, cost and management frameworks; evaluate the phase.	Property Management
Decision point 3 (BP3)	Decide on the start of the execution phase, approve management documents, and make an investment decision	Property Management
Execution phase	Implement the project in accordance with the BP3 decision.	Property Management
Decision point 4 (BP4)	Decide whether closing activities may begin, and whether deliverables can be handed over to operations.	Property Management
Closing phase	Finalise all remaining activities, formally close the project, and hand over to Operations.	Property Management
Decision point 5 (BP5)	Decide whether the project can be closed; approve the final report.	Property Management
Realisation	Normal operations and benefits realisation at the service location.	Property Management
Decision point 6 (BP6)	Evaluate the benefits realisation plan and decide on any further actions.	Property Management

The project framework has phases with decision points for progression, covering needs assessment through benefits in municipal operations. Responsibilities are divided between property management and service units (such as schools, kindergartens, and care facilities).

The process begins with municipal service units conducting a pre-analysis to determine whether a project is necessary. Property Management then assesses and approves development through decision points. During the concept and planning, Property Management prepares mandates, documentation, feasibility assessments, and cost frameworks before deciding to proceed. The execution phase implements the approved work. After completion, the project enters the closing phase, finalising activities and handing over to operations. Operation and benefits are later evaluated at the final decision point. This structured approach ensures transparency, clear distribution of responsibilities, and systematic decision-making throughout the project lifecycle.

3.2 Municipal Strategic Documents and Circularity Goals

The municipality has a climate strategy, supported by an action plan on CE, with clear goals and measures. The climate strategy is organised into four parts: objectives, initiatives, sub-goals, and measurements. One of the three main goals related to CE states that "By 2030, the municipality is established as a leading municipality in the CE."

Included in the CE measures are shifting from a linear to a circular process, reducing consumption, flexible solutions, and increased joint use, inclusion of reuse in all processes, preserving existing buildings, and implementing reuse in new construction and rehabilitation.

3.3 Project Documentation and Governance Framework

Table 2 provides an overview of the relevant written descriptions and documents used in the municipality's project work, along with their respective explanations.

Table 2. An overview of relevant tools and documents for CE implementation in projects.

Type	Name	Description
Tool	Plania	Facility Management System. Including descriptions of proposed measures for a property
Project description	Simple mandate: Project suggestion for BP2	Preparation of a project proposal, including costs and ambition levels
Framework	Book 0	External Frameworks and Overarching Cross-disciplinary Requirements
Framework	Book 1	Room and Functional Programme for Buildings and Outdoor Areas
Framework	Book 2	Common Technical and Outdoor Works Specification

The systematic review of the relevant documents revealed that there are no current requirements requiring reuse to be considered at any stage of the project process. The

project proposal mandate does not mention reuse, and the extent to which it is explored largely depends on individual project managers.

The BP2 documentation currently includes a brief description of the measure and an estimated cost, retrieved from the Facility Management System (FMS). Needs assessments and prioritisations are carried out across buildings by the management team, but reuse considerations are absent at this stage. Book 0 outlines technical descriptions, colour schemes, height specifications, and universal design requirements, none of which incorporate reuse. Requirements related to flexibility, elasticity, and generality may indirectly hinder reuse, as they demand robust construction and can increase costs.

Across rehabilitation and new construction, numerous functional requirements must be met, including daylight requirements, room sizes, universal design, and technical standards.

3.4 Interview Data

The interview findings indicate the stages of the municipal building project process, outlined in Table 1, at which potential barriers and opportunities for facilitating material reuse may arise. Moreover, they reveal how the various regulatory documents listed in Table 2 could impede or enable the implementation of reuse throughout the construction process.

Interview data indicate that current mandates from property management often require full component replacements for consistency. Limited budgets favour full replacements, as partial upgrades are operational expenses, whereas replacements above a threshold can be capitalised, thereby accessing more funds. Standard descriptions, therefore, generally specify purchasing new materials and replacing old ones. In addition, users prefer new materials, which affects the feasibility of reuse.

Practice examples show architectural drawings often cause unnecessary purchases. Interviewees note that architects base designs on the room and area programme (Book 1), which lists materials, performance requirements, durability standards, and furniture. This can lead to ordering new materials instead of reusing. They also highlight the need for early clarification meetings to align expectations and find reuse opportunities. Access to suitable reused materials is also recognised as a practical barrier.

Informants emphasise the need to adapt existing property management routines to better support reuse. In new construction projects, the responsibility for incorporating reused materials generally falls to the contractor, though high aesthetic standards set by stakeholders can limit the acceptance of reclaimed materials.

4 Discussion and Conclusion

4.1 Municipal Governmental Policy Barriers and Enablers of Reuse Practices

Despite the municipality's overarching goals for reuse and circularity articulated in its strategy and action plan, there appears to be a gap between these policy objectives and the practical introduction of reuse requirements. The complex municipal project process involves many sequential steps and multiple resources, which can lead to reuse intentions and measures being lost or weakened by the time the final construction project is completed.

The findings indicate that, although the municipality undertakes a wide range of construction and rehabilitation projects aimed at increasing and prioritising reuse, existing governance structures and routines pose significant barriers to material reuse. Current mandates and budget mechanisms promote full replacement rather than selective upgrading, and user expectations for entirely new materials further point to this tendency. These patterns could indicate how organisational and cultural norms can restrict the adoption of circular practices, even before technical challenges arise.

The absence of formal requirements to assess reuse at stages of the project process could result in circular measures that depend on individual initiative rather than on institutionalised practice. This dependence on individuals is further reinforced by governing documents that do not address reuse. Consequently, opportunities for reuse would rarely be identified systematically.

High aesthetic expectations, universal design constraints, and technical standards contribute additional structural limitations. While these requirements rightly ensure quality and accessibility, they also appear to limit flexibility in integrating reused components, especially when governing documents assume "new" as the default. Because these requirements aim to increase the longevity and usability of buildings, demands such as flexibility, elasticity, and generality can become significant barriers to reuse if prioritised without adopting a reuse mentality.

4.2 Adoption of Municipal Processes to Meet Circularity Goals

Based on the interview results, it appears that current processes and documents do not consistently uphold the overarching circularity goals, and there is potential to improve existing procedures to ensure that documents and project phases support material reuse throughout the project's lifespan.

The findings appear to show a misalignment between executing processes and circular ambitions. If a contractor relies on predefined room programmes and material specifications that prioritise robustness and uniformity, opportunities for reuse may be overlooked. This suggests that circular practices may be embedded not only in policy documents but also in operational tools and professional routines, including the project process steps.

Overall, the findings indicate that adopting reuse in municipal construction could benefit from a coordinated revision of governance documents, decision-making routines, financial incentives, and professional practices. Clarification meetings and early-phase discussions could help identify reuse opportunities before design choices lock the project into linear solutions. Systematic integration of reuse assessment in project phases would provide a more structured foundation for circularity and reduce the reliance on individual actors.

4.3 Limitations

The study's limitations include limited generalisability due to its focus on one municipality, which may restrict its applicability. Only a few municipal officials were interviewed, so the results pertain exclusively to public-sector construction. However, this municipality's size, experience, and challenges are similar to those of many Norwegian and other

Nordic municipalities. Insights are likely transferable due to legal and sector similarities. There is some risk of bias in participant selection, but municipalities usually have dedicated thematic roles, making interviewees relevant. projects.

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Stakeholders and Collaboration Models: Roles, Interactions, and Governance Mechanisms for Systemic Change

Closing the Nutrient Loop: Circular Economy Valorization of Swine Lagoon Sludge into Fertilizer for GHG Reduction and Soil Regeneration

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Abstract. As one of the sectors with the most significant negative environmental impact, agriculture and livestock production account for approximately 70% of global freshwater consumption and 30% of total greenhouse gas (GHG) emissions. In this context, solutions that not only mitigate environmental damage but also actively regenerate ecosystems are essential for sustainable food production. This study presents a circular and integrated approach for managing biosolids (sludge) accumulated in swine farming lagoons and biodigesters, transforming a waste by-product into a valuable agricultural input. The methodology employs the SERVARE® SYSTEM, a multi-stage circular process: (1) Cleaning: removal of accumulated sludge from lagoon beds; (2) Stabilization: mixing the sludge with a structuring agent to facilitate drying and stabilize organic matter; (3) Drying and stabilization: final processing of the material; and (4) Final Destination: application of the processed biosolid as an organic fertilizer in crops, thereby closing the nutrient loop. This practice is highly relevant to regenerative agriculture, as it promotes nutrient circularity within the production system. Reintroducing biosolids into the soil reduces dependence on mineral fertilizers and enhances soil health, effectively closing the cycle "from waste to nutrient." Thus, contributing to a more resilient and sustainable model for food production and security. It is concluded that the sludge, once considered a liability, constitutes a valuable source of organic matter, nitrogen, and phosphorus. Its transformation into fertilizer is technically feasible, strategically sound, and economically viable, establishing it as a circular business model.

Keywords: Biosolids Management · Nutrient Circularity · Industrial Symbiosis · Regenerative Agriculture · Sludge Valorization,Introduction

Brazil's persistent reliance on imported chemical fertilizers, which currently supply approximately 85% of national demand, constitutes a strategic vulnerability with multiple dimensions. This dependency, exacerbated by geopolitical crises and international market disruptions, as evidenced by supply disruptions caused by the conflict in Ukraine,

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exposes food security and the competitiveness of Brazilian agribusiness to systemic risks [1]. At the same time, a fertilization model based on high-energy-intensity imported inputs conflicts with pressing environmental imperatives and the growing global demand for sustainable and resilient agri-food systems.

In this challenging context, there is an urgent need to systematize viable and innovative alternatives grounded in circular economy principles, including the expansion of bio inputs, the adoption of regenerative agricultural practices, improvements in nutrient-use efficiency, the valorization of waste-derived sources, and the development of domestic fertilizer sources, in order to advance strategic autonomy and a meaningful transition toward a more sustainable Brazilian agriculture [1].

Within this scenario, Brazil is also a major global livestock producer. In 2024, the national swine herd was estimated at approximately 37 million animals according to data from the Brazilian Ministry of Agriculture, Livestock and Food Supply (MAPA) [2], being the leading swine producer in Latin America.

Swine production generates substantial volumes of liquid effluent, whose treatment yields a significant by-product: sludge. This sludge accumulates progressively at the bottom of stabilization lagoons, biodigesters, and sedimentation tanks, where suspended solids are removed, and organic matter is degraded [3]. If not periodically removed, sludge accumulates at the base of stabilization lagoons and biodigesters, reducing hydraulic retention time (HRT) and degrading treatment efficiency, constituting a potential source of uncontrolled GHG emissions [4]. Yet swine lagoon sludge is simultaneously rich in nitrogen, phosphorus, and calcium, conferring substantial agronomic potential when properly managed

It is in this dual context, operational necessity and resource recovery opportunity, that the present study situates itself. The approach proposed herein seeks to overcome the limitations of conventional isolated-stage treatment methods by implementing an integrated, continuous flow from sludge removal to the production of a standardized, commercially viable organic fertilizer. A key distinguishing feature is the use of eucalyptus wood shavings derived from construction-site formwork waste as the composting structuring agent, establishing an industrial symbiosis that simultaneously valorizes residues from two distinct sectors. This work thus bridges the built environment and agro-industrial domains, offering a replicable circular business model aligned with SDGs 9, 12, 13, and 15 [5]. The present study, therefore, aims to develop and validate an integrated system for the sustainable conversion of swine lagoon sludge into high-quality organic fertilizer, underpinned by field monitoring and laboratory analysis throughout a 120-day composting cycle.

1 Background

1.1 Polluting Potential of Swine Lagoon Sludge

The principal residue generated during the treatment of swine effluent, regardless of production scale, from family farming to large integrated operations, is sludge. This by-product results from multiple treatment stages, including sedimentation tanks, stabilization lagoons, and biodigesters, in which suspended solids are removed, and organic

matter is degraded. During these processes, significant volumes of sludge form and settle gravitationally at the base of treatment structures [3].

Sludge is composed of organic and inorganic solids, including significant concentrations of agronomically relevant nutrients such as nitrogen, phosphorus, and calcium. Over time, treatment systems accumulate substantial quantities of sludge at the bottom of lagoons and biodigesters, causing progressive siltation that drastically reduces the effective depth and operational volume of these installations.

This reduction in effective volume diminishes the effluent residence time within the treatment system, referred to as Hydraulic Retention Time (HRT). A reduced HRT, resulting from sludge accumulation, negatively affects treatment efficiency and may constitute a significant source of environmental degradation, including uncontrolled GHG emissions [4]. Periodic sludge removal is therefore both an operational and environmental imperative.

1.2 Circular Economy Framework and Nutrient Recovery

It is important to emphasize that the sludge recovered during lagoon cleaning operations has a high organic matter content, rendering it potentially valuable as an agricultural input. In this respect, its valorization aligns directly with the objectives of Brazil's National Fertilizer Plan 2022–2050 (*Plano Nacional de Fertilizantes*), which aims to reduce the country's external dependency on fertilizers, currently exceeding 80% of national consumption [6]. Strategic initiatives such as the one presented in this study can help meet a substantial portion of domestic demand, thereby reducing vulnerability to external factors and strengthening the economic autonomy and cost stability of rural producers.

When applied in accordance with agronomic criteria, the organic matter present in swine sludge can effectively replace mineral fertilizers by increasing crop yields, enhancing soil physical, chemical, and biological properties, and reducing agricultural production costs [7, 8]. However, inadequate management or application rates exceeding the soil's nutrient-recycling capacity may generate negative environmental externalities, including GHG emissions, nutrient leaching and surface runoff, and contamination of soil and water bodies with pathogens.

The circular economy framework underpinning this study treats the swine lagoon sludge not as a liability but as a secondary raw material embedded within a closed-loop system. This reframing is consistent with the Ellen MacArthur Foundation's [9] principles of designing out waste and maintaining materials at their highest utility, applied here at the scale of an individual agro-industrial production system. The proposed integrated approach, encompassing sludge removal, stabilization, composting, and agronomic reuse, constitutes a continuous and increasingly automated flow that transforms a previously unmanaged waste stream into a standardized, high-value commercial product. Therefore, the SERVARE® SYSTEM operationalizes this principle through a continuous, increasingly automated process chain from sludge extraction to market-ready compost.

1.3 From Construction Site to Soil: Valorizing Wood Waste as a Composting Agent

Wood waste from construction site formwork and falsework, typically disposed of in landfills, can be valorized as a bulking agent in swine sludge composting. The literature demonstrates that composting and bioremediation techniques offer a viable pathway to divert construction and demolition (C&D) wood waste from landfills and transform it into a useful, value-added product [10]. The scale of this opportunity is significant: Brazil generated approximately 48 million tonnes of construction and demolition waste (CDW) in 2021, representing 71% of the country's total waste stream, yet formal recycling rates remain critically low [11, 12]. Wood constitutes a meaningful fraction of this stream, with construction formwork and falsework timber representing a recurrent, regionally concentrated source of lignocellulosic residues that are routinely destined for landfill or uncontrolled disposal [11].

Shredded wood provides the porosity necessary for adequate windrow aeration while balancing the high nitrogen content of swine effluent through its elevated carbon fraction [10]. The resulting C: N synergy promotes robust thermophilic microbial activity, accelerating organic matter degradation and producing a stable, sanitized, nutrient-rich compost suitable for agricultural use. This cross-sector approach converts environmental liabilities from civil construction and swine production into value-added agricultural inputs, exemplifying industrial symbiosis and the broader circular economy principle of cross-sector resource retention, a practice of direct relevance to regenerative built environment strategies. Furthermore, it offers a replicable model for other regional agro-industrial contexts where similar waste streams co-exist.

2 Materials and Methods

The study was conducted in Brazil, in a specific agricultural region of Minas Gerais state. The sludge was sourced from an anaerobic stabilization lagoon (30 m × 75 m × 4 m) serving a commercial swine facility housing 2,000 breeding sows. The lagoon had not undergone sludge removal for eight years. Sludge was extracted by pump and transported to a composting yard. Three replicate windrows were constructed in a pyramidal configuration (base 4 m, height 2.5 m, length 50 m). Eucalyptus wood shavings (Eucalyptus grandis), obtained from the processing of formwork and falsework timber recovered from reinforced concrete construction sites, were used as the structuring agent and carbon source.

Internal windrow temperatures were monitored throughout. Windrows were mechanically turned weekly until Day 50 and at 21-day intervals thereafter to ensure homogenization. Composite samples were collected at the start and end of the 120-day composting period and analyzed for moisture content, C: N ratio, nitrogen, phosphorus, potassium, and pH, following the AOAC [13] standard methods. Results were benchmarked against the Brazilian Normative Instruction IN 61/2020 [14], which governs the quality standards for organic fertilizers derived from composting.

3 Results and Discussion

Table 1 presents the mean initial and final physicochemical values recorded throughout the composting cycle, along with the regulatory thresholds in IN 61/2020 [14].

Table 1. Initial and final parameters of swine sludge composting with eucalyptus wood shavings from construction site waste.

Parameter	Initial	Final	Regulatory Standard (IN 61/2020)
pH	6.2	8.6	Minimum 7.0
Moisture (%)	76.4	35.3	Maximum 50%
C: N Ratio	36.1	16.8	Maximum 20
Nitrogen (%)	2.3	1.8	Minimum 0.5%
Phosphorus (%)	19.8	18.2	As declared
Potassium (%)	0.9	0.7	As declared

All physicochemical parameters analyzed met the quality requirements stipulated by the Brazilian Ministry of Agriculture, Livestock and Food Supply (MAPA) [2] for organic composts. Notably, windrow temperatures exceeded 55 °C for more than 30 days, which is sufficient to ensure the biosafety and sanitization of the final compost by eliminating pathogenic microorganisms, a critical prerequisite for agricultural land application.

With respect to pH, the final mean value of 8.6 exceeds the regulatory minimum of 7.0. It indicates an alkaline reaction that may offer agronomic benefits in the context of Brazil's predominantly acidic agricultural soils. Although the initial moisture content was elevated (76.4%), the composting process reduced it by more than 40 percentage points, yielding a final moisture content of approximately 35%, well within the regulatory threshold of 50%. This substantial reduction in moisture content reduces transportation costs and facilitates field application, as it also results in a greater concentration of nutrients per unit mass.

The C: N ratio declined from 36.1 at the outset to 16.8 at the end of the composting cycle, falling below the regulatory maximum of 20 and reflecting the progressive mineralization of organic carbon and the maturation of the compost. The final nitrogen concentration of 1.8% exceeded the regulatory minimum of 0.5%, and potassium values demonstrated suitability for agricultural use, consistent with findings reported by Martins et al. (2022) [8] for composts incorporating agro-industrial residues.

Notably, the recorded phosphorus concentrations exceeded 15% throughout the process. For reference, Simple Superphosphate, one of the most widely used phosphatic fertilizers in Brazilian agriculture, contains approximately 18–21% P_2O_5. The phosphorus content of the organic compost produced in this study is therefore comparable to that of commercially prevalent synthetic fertilizers, representing a significant finding with practical implications for the substitution of mineral inputs. This cross-sector valorization process thus emerges as a highly promising strategy for the simultaneous recycling

of two distinct waste streams: swine production effluent sludge and construction site wood waste.

Of particular relevance is the industrial symbiosis established by the proposed approach, in which shredded wood waste recovered from the construction industry is incorporated into the composting process as a carbon source to stabilize swine effluent sludge. This cross-sector symbiosis transforms residues from two economically significant industries into productive agricultural inputs, simultaneously reducing waste disposal costs and decreasing dependence on externally sourced raw materials. The environmental benefits are material and partially quantifiable: anaerobic lagoons are among the most significant sources of agricultural methane, with swine manure management estimated to contribute 64.7 MMT CO_2 equivalent globally in 2022 [15]; diverting sludge from unmanaged lagoon storage to composting has been shown to conserve an equivalent of up to 3.1 Mg CO_2eq per dry tonne of feedstock composted when materials are diverted from lagoons without gas collection [16]. The model thereby advances circular economy objectives by closing two independent waste loops simultaneously, yielding quantifiable GHG reductions and mutually beneficial economic outcomes for both the construction and swine production sectors.

4 Conclusion

The composting of swine lagoon sludge with eucalyptus wood shavings recovered from construction site formwork waste is technically feasible, environmentally strategic, and economically viable. The resulting compost met all quality parameters of IN 61/2020 [14]: biosafety was assured by sustained thermophilic temperatures; moisture reduction optimized logistics; an alkaline pH offers potential for correcting acidic soil; and phosphorus concentrations were comparable to those of widely used commercial mineral fertilizers.

From a circular economy perspective, the process consolidates an integrated cross-sector solution, closing the nutrient loop while simultaneously diverting construction wood waste from landfill through industrial symbiosis. The avoidance of uncontrolled methane generation from unmanaged sludge lagoons, combined with the displacement of energy-intensive synthetic fertilizer production and the diversion of construction wood residues from landfills, yields compounding, partially quantifiable GHG reductions across both sectors. Industrial symbiosis of this kind is recognized as a key strategy for implementing circular economy principles across value chains and business sectors, achieving simultaneous economic, environmental, and social benefits [17, 18]. As a scalable circular business model aligned with Brazil's National Fertilizer Plan 2022–2050 [6] and the SDGs, the SERVARE® SYSTEM offers a replicable pathway particularly suited to Brazil's agro-industrial landscape, where swine production clusters and active construction activity frequently co-exist within the same regional economy, creating the geographic proximity and complementary waste streams that are prerequisite conditions for effective industrial symbiosis [11]. Future research should prioritize life cycle assessment of the full process chain to quantify net GHG savings, long-term agronomic performance trials, and the development of digital monitoring tools to support the scaling and standardization of sludge valorization systems.

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From Project to Ecosystem: A Collaborative Value Chain Framework for Circular Building Implementation

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Abstract. Transitioning to Circular Building (CB) is essential for reducing the built environment's impact on planetary boundaries; however, a lack of conceptual clarity and practical guidance for practitioners hampers its effective implementation. This research bridges the gap between theoretical circularity and industry practice by developing a collaborative framework grounded in empirical evidence. The study uses a qualitative inductive approach, synthesising academic and industry literature with an in-depth analysis of 28 global case studies. Data were collected through expert interviews, site visits, and project documentation from pioneering firms in Europe, Japan, and Oceania across architecture, engineering, urban redevelopment, and Modern Methods of Construction (MMC). The findings show that effective circularity cannot be achieved through isolated project delivery methods but requires an ecosystem approach. A key insight is the need for a collaborative innovation strategy in which stakeholders must map and engage with local value chain ecosystems (including material suppliers, reverse logistics, and secondary marketplaces) before beginning the design process. The research presents a new conceptual framework that defines CB typologies and material classes, moving beyond abstract principles to focus on practical collaboration. The study concludes that mainstreaming CB demands a shift from project-focused thinking to ecosystem-centred collaboration. This research provides a pathway for Building Value Chain (BVC) stakeholders to work together to operationalise circularity. Rather than fragmented efforts, the findings emphasise the importance of regenerative practices throughout the BVC.

Keywords: Circular Economy · Circular Building · Circular Building Ecosystem · Value Chain Collaboration · Case Study Analysis

1 Introduction

Globally, the construction industry is often cited as a substantial contributor to climate change, resource depletion, and waste generation [1, 2]. Given the well-established potential of CB adoption for mitigating the built environment's significant impact on the planetary boundaries, transitioning from the current linear to CB is critical [3, 4]. CB is an approach to building that can substantially mitigate emissions, water and energy consumption, and waste generation by reducing raw material use and preventing waste. Yet,

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practical implementation is hindered by conceptual ambiguity and a lack of actionable guidance for building sector stakeholders [5].

One of the topics requiring further conceptual clarity and guidance, cited in academic research as a tool to boost innovation, productivity, and circularity, is collaboration among project stakeholders [6]. Some authors claim that applying collaborative innovation and integrative partnerships among stakeholders across the value chain can contribute to sustainability by optimising processes, improving resource efficiency, and promoting eco-innovation [7]. However, while academic literature consistently advocates for collaboration as a critical component of circularity, innovation, productivity, and sustainability improvement, a more profound understanding of, or guidance on, the type of collaboration required is rare [6]. On the other hand, the lack of teamwork, unreliable planning, and a tendency to transfer risk are consistently identified as factors contributing to low productivity and efficiency in the construction industry. Since the construction sector is often characterised by a lack of mutual trust, fragmentation, and adversarial relationships, a deeper understanding of collaboration and the strategies needed to implement it effectively in CB projects is needed [8].

Given that CB requires the active involvement of multiple stakeholders, understanding the complex relationships underpinning real-world projects is crucial to effective realisation. Although the call for collaboration is a common topic in academic literature, no reference provides clear definitions of the extent of collaboration required, when it is required, or with whom. New models, such as 'coopetition', enhance performance by enabling stakeholders in business ecosystems to cooperate and compete simultaneously, while building mutual trust and sharing knowledge and resources [9].

This paper aims to clarify the collaborative processes and interrelationships required for CB implementation. Its findings contribute to understanding CB through a business ecosystem approach rather than as an isolated firm endeavour, and provide practical guidance for its implementation. The comprehensive data analysed include various case studies that support these findings, and the proposed constructs bridge the gap between theoretical circularity and industry practice by developing a practical ecosystem framework rooted in empirical evidence.

2 Methodology

This research employs a qualitative, interpretive methodology, underpinned by a Design Science Research framework, to move from problem identification to the development of a practical decision-support artifact, the CBE. The research design follows a multi-stage, inductive process that triangulates three primary data streams to ensure methodological rigour and construct validity:

- Academic Meta-synthesis: A systematic search of peer-reviewed review papers (2014–2024) was conducted on Web of Science, Scopus, and Google Scholar, following PRISMA guidelines.
- Grey Literature Scoping Review: An analysis of 34 industry roadmaps, policy documents, and toolkits was undertaken to capture current practitioner standards and identify gaps between academic theory and industry guidance.

- Case Study Analysis: An empirical enquiry was conducted involving 28 international cases across seven building specialties. Data collection included semi-structured expert interviews, site visits, and project documentation from CB pioneering firms in Europe, Japan, and Oceania across the architecture, engineering, and MMC sectors.

A pragmatic interpretive approach was used to prioritise actionable outcomes from the data, which was analysed using a combination of Inductive Content Analysis and Reflexive Thematic Analysis. Qualitative coding was managed through NVivo, progressing from descriptive labels to the generation of patterns of meaning and conceptual constructs. To synthesise these complex datasets, the study utilised extensive concept mapping to visualise the interrelationships between stakeholders and their involvement in the CB project lifecycle stages. The reliability of findings was maintained through a rigorous reflexive accounting process, including constant comparison of codes and manual transcript verification to prevent definitional drifting.

3 Results

The results confirm that effective circularity cannot be achieved through isolated project delivery methods but requires a collaborative approach. The case studies demonstrate that CB cannot be delivered by individual firms working in silos but requires a CBE—a network of collaborating organisations. Project delivery must shift from adversarial contracting to collaborative models like integrated design or joint ventures. This enables shared risk management of secondhand material warranties and fosters the trust required for innovation. While firms routinely collaborate in the BVC to build projects, the case studies reveal nuances in the type of collaboration required to deliver CB projects. Four collaborative features that emerged from the data will be explained in the following subsections in more detail:

- CBE mapping,
- Collaborative project delivery,
- Innovation management, and
- Procurement partnerships.

3.1 Circular Building Ecosystem Mapping

A defining strategic challenge for any CB project is mapping the availability of a network of stakeholders, including architects, consultants, engineers, software developers, construction material retailers, recyclers, and facility managers who enable CB implementation, even those not directly involved in a specific project. For instance, a reverse supply chain is necessary to move reused construction materials back into another construction project, and a system is required to allocate those resources where they are needed for new buildings. Therefore, understanding the local or regional context of circularity in the value chain is critical to CB implementation, as it requires an industry-wide ecosystem of collaborating organisations—a CBE. Contextual factors such as the availability of a nearby CBE may help circularity emerge, and the geographical proximity of a CBE appears to be one reason for the proliferation of CB in Europe, alongside cultural and public policy factors. For example, online marketplaces emerging in Northern Europe

enable connections between multiple donors and multiple potential buyers of second-hand materials. These contextual elements significantly impact CB implementation and must be understood before making any further project decisions.

CBE mapping entails understanding the context of circularity in which a project is being developed. It involves assessing the local availability of recycling facilities and product reuse platforms, the broader circular economy market, and analysing policies that support the uptake of these products, as well as the pricing of waste management and product cycling. The proposed CBE diagram in Fig. 1 helps identify the critical activities, value chain interdependencies, and material flows required to implement CB at a strategic level and to adjust the missing elements to the project's context.

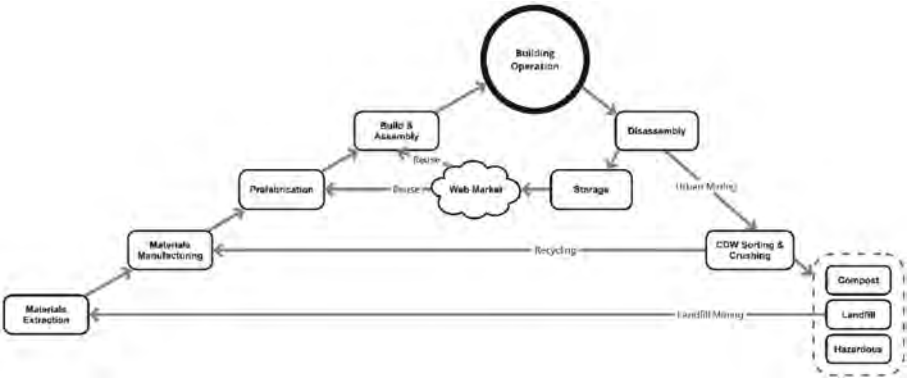


Fig. 1. Proposed Circular Building Ecosystem diagram.

In Fig. 1, each activity box represents a diverse set of sub-activities led by multiple stakeholders, a typical feature of the BVC. It also helps visualise value creation, value loss, and value retained in material transfers: upward arrows represent value added, downward arrows represent value loss, and horizontal arrows indicate value-keeping activities. The diagram addresses the challenge of understanding the business network capabilities required to enable effective resource looping. However, it does not claim that every actor must be available for it to work effectively. It is not intended to be prescriptive but to serve as a tool to aid effective CB implementation. Some relevant aspects of the diagram include:

- Beyond mapping, the CBE diagram enables effective planning of the activities needed to realise CB.
- The diagram highlights the activities rather than the stakeholders responsible for them, as stakeholders might change over time.
- Recycling is not presented as an activity in itself, but as the process of reintroducing materials back into the manufacturing loop.
- Introducing prefabrication as an activity acknowledges that contemporary construction involves various levels of MMC and recognises MMC's potential to advance circularity further [10].

- Often-overlooked activities such as Storage and Web Market were found to be critical through the case study research.

3.2 Collaborative Project Delivery

A collaborative or integrated process fosters alignment among project stakeholders by establishing a shared ambition from early planning through design and construction. The cases studied in this research identified that at least two willing and collaborating stakeholders (typically an architectural firm and a contractor or circular-materials specialist) are indispensable for initiating a CB project, but need the support of a critical third stakeholder: the client. The study of the client's motivations suggests that their initial aims are a vital enabler of circularity. These motivations are commonly oriented toward pursuing innovation that advances beyond typical sustainable design. In such cases, clients award contracts to firms that offer circularity and innovation to push the boundaries of sustainability.

Digitisation through BIM, Digital Twins, and Material Passports has emerged not just as an efficiency tool but also as a prerequisite for circularity, helping counter the fragmentation of the BVC. Enabling material visibility across the project lifecycle and BVC stakeholders helps track material flows and the creation of secondary marketplaces. Other practical recommendations include:

- Harnessing the expertise of a broad group of stakeholders, including material manufacturers, clients, designers, engineers, product suppliers, demolition contractors, and builders, is paramount to sound decision-making from the early stages. However, who to include and when must be tailored to each project's needs.
- The project contract must establish a 'collaboration space' to enable and manage the risks associated with implementing innovative, new, untested ideas that require 'Innovation Management'.

3.3 Innovation Management

Since CB often emerges as an innovation pursuit that involves strong collaboration across the CBE, building trust and effective decision-making processes is crucial, but collaboration becomes harder as the number of partners grows. Finding like-minded, complementary partners with whom to collaborate in close, innovation-focused, integrative partnerships appears essential but hard to achieve.

Some of the best examples of well-aligned value chains are provided by MMC firms such as Boklok, Gropyus, Misawa Homes, Sekisui Heim, and Sekisui House, all of which maintain vertical value-chain integration or long-term, close partnerships with suppliers. Since MMC firms' experience positions industrialisation as a strong enabler of circularity, this study identifies a strong combined effect between MMC and CB. MMC is also essential for producing "DfAD-Ready Products"—standardised, interchangeable components such as cassettes or pods that facilitate rapid assembly and, crucially, disassembly. This requires a shift from 'construction' to 'assembly' and from unique projects to standardised processes and components.

An innovation strategy is instrumental for addressing a project's specific contextual elements and developing a comprehensive roadmap towards its long-term objectives.

This involves managing a circular value chain to enable partnerships within business clusters and to support reverse logistics for the circulation of secondary materials. An innovation strategy is a direct response to the context and the project's defined business model, enabling the project team to strategically identify the key partnerships and operational approaches needed to achieve its goals. At the firm level, the ability to collaborate and partner with other firms is crucial to building the business relationships that enable CB. Since innovation poses additional risks to those handled in traditional building projects, some practical recommendations garnered from the study include:

- When a specialist stakeholder is not available within the local ecosystem, the required function can be absorbed by the firm responsible for the project.
- It is advised to start with small pilot projects and then show results and replicate.
- Set a separate 'innovation budget' for high-risk ideas.
- Set timing, processes and testing methods for innovative materials from the start. For instance, quality testing is critical for the reuse of secondhand materials.
- Set a dialogue-based decision-making process with go/no-go milestones.
- Innovation needs to be stimulated through the procurement methods, which leads to the next topic.

3.4 Procurement Partnerships

Collaborative tendering usually involves establishing a transparent, straightforward process that clearly stipulates the expected circular outcomes, while adopting an open tendering approach that allows bidders to propose solutions with minimal uncertainty. Other common features include a negotiation phase to discuss and assess ideas and their rationale before signing the contract, thereby promoting bidirectional knowledge sharing between the client and the bidders.

Commercial partnerships enable greater reach and scale for specialist stakeholders, such as disassembly, storage, or web market brokers. This type of value chain collaboration is critical to fostering secondary materials markets, standardising material testing, creating a materials database, establishing a market with a network of recycling organisations, integrating value chains into product creation, and managing market perceptions. Various forms of partnerships are recommended when planning a project's circular business model. One of those is the coopetition model, typical of business ecosystems working in clusters or hubs, where firms share knowledge and other vital resources [7, 9]. Other partnership forms include joint ventures, in which two or more firms form a strategic alliance to collaborate on a specific project and share resources, risks, profits, and losses. Some general recommendations include:

- Alignment of goals and values is essential for building trust, from the bidding phase onwards.
- Joint ventures between two equal partners are the easiest to manage, while a larger number of stakeholders in a partnership adds extra risk and complexity.
- Alignment of the value chain is crucial to ensure that circularity occurs in the future; it will be determined by the stakeholders present at the end-of-use.
- BVC alignment is crucial because circularity is essentially a promise of something expected to happen in the future; it will be determined by the stakeholders present at

the end of the project's use. This is enabled through shared digital models, material passports and circular supply chains (e.g., industrial symbiosis or reverse logistics).

4 Discussion and Conclusion

The study concludes that mainstreaming CB requires a paradigm shift from project-centric thinking to ecosystem-centred collaboration. A collaborative approach is vital for overcoming the structural and organisational fragmentation of the BVC, as well as the knowledge loss from one project to the next, both of which have historically hindered innovation in the industry. This study introduces four constructs and a CBE framework to clarify the collaborative processes and interrelationships required for CB implementation.

The CBE helps identify the stakeholders missing for CB to work, regardless of the local BVC's level of development or preparedness, and to prepare an adequate response to that context. The collaborative innovation strategy addresses contextual elements through CBE mapping and strategises to fulfil the long-term project goals, aligned with the project's business model. The mapped CBE clarifies the project's specific context, and the business model outlines its aims and objectives, which the project team uses to set a strategy to achieve those goals and to define with whom to partner and how. Therefore, the collaborative innovation strategy is a response to the findings of the CBE mapping, the project's business model, and the project team's strategic definition. Once clarity is obtained on the features of the local and regional CBE, more detailed decision-support guidelines are needed to describe the activities required for each stakeholder throughout the project's lifecycle.

Although collaboration is common and necessary in the BVC's traditional work processes, the kind of collaboration needed in CB is characterised by high levels of trust and transparent, honest communication. Previous BVC collaboration models, such as Integrated Project Delivery, have successfully developed methods and processes to enable improved outcomes through close stakeholder collaboration [11]. The CBE suggests that more stakeholders may be required, directly or indirectly, at the decision-making table—potentially including even material (re)manufacturers.

This paper's main contribution lies in clarifying some nuances and practicalities of effective CB implementation, summarised in the following six points:

- At least two willing and collaborating stakeholders are needed to initiate a CB project, who are often aligned around a shared ambition and require the support of another essential stakeholder: the client.
- Three critical stakeholders drive circularity: the client, the architectural firm (which often is CB-focused), and a specialist contractor.
- CBE mapping provides information on the relevant business, cultural and policy context for the project.
- The project team must develop a project business model and an innovation strategy that responds to the CBE mapping to implement the business model.
- An innovation strategy helps manage the risks of using new, untested processes and secondhand materials. It also comprises the procurement strategies and key partnerships needed for the project.

The actionable guidance on collaboration for CB implementation in this paper addresses a much-needed knowledge gap and invites future contributions to mainstream circularity by further detailing the processes and workflows involved.

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Mapping Stakeholder Information Needs to Enhance Energy Efficiency, Circularity, and Sustainability in the Built Environment

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Abstract. Achieving more sustainable and circular practices in the construction sector requires a clear understanding of the information needs of the stakeholders involved throughout the building lifecycle. This study investigates the data requirements, roles, and decision-making needs of key actors in the European construction sector, including architects, engineers, contractors, energy consultants, regulators, facility managers, and material suppliers. The research adopts a mixed-method approach combining an online survey and targeted interviews. The survey, distributed across Europe through professional networks and social media channels, collected 101 responses from construction-sector stakeholders. In addition, 13 semi-structured interviews have been conducted to deepen the understanding of stakeholder perspectives and contextualize survey results. The collected data have been analyzed through data-mining techniques and visualized through graphical representations to identify patterns in information needs, preferred data formats, and decision-support requirements. The results highlight differences among stakeholder groups in terms of required information types, levels of technical detail, and preferred delivery formats. These findings support the development of structured information workflows that better align data provision with stakeholder responsibilities and decision-making processes. By clarifying stakeholder information requirements, the study contributes to improving data management practices and supporting the implementation of sustainable and circular strategies in the built environment.

Keywords: Energy resource efficiency · Sustainability · Circularity · Building life cycle · Digitalization

1 Introduction

The construction sector plays a central role in the transition towards a more sustainable and resource-efficient built environment. In the European Union (EU), buildings account for a significant share of energy consumption and greenhouse gas emissions, making the

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sector a key focus of climate mitigation and circular economy strategies [1]. European policies such as the European Green Deal [2] emphasize the need to improve building performance, enhance resource efficiency, and lifecycle-based approaches to building management.

To support these objectives, the European Union is increasingly promoting the digitalization of the construction sector as a key enabler for more efficient data management and decision-making processes. Initiatives such as Digital Building Logbooks (DBLs) and Digital Product Passports (DPPs) aim to improve the availability, traceability, and interoperability of building-related information throughout the lifecycle of assets [3]. These digital approaches facilitate better monitoring of building performance, improved resource management, and the implementation of circular economy principles within the built environment [4].

Despite these developments, the effective management and exchange of information within the construction sector remain significant challenges. The sector is characterised by a high level of fragmentation, involving multiple actors operating across different project phases, organizations, and digital environments [5–7]. Architects, engineers, contractors, facility managers, regulators, material suppliers, and energy consultants all contribute to generating and managing building-related data, yet they often rely on different standards, tools, and workflows. As a result, information is frequently stored in isolated systems or exchanged through non-standardized formats, limiting its accessibility and usability for other stakeholders involved in the building lifecycle [8, 9].

In this context, understanding the information needs of stakeholders in relation to specific topics becomes a critical prerequisite for improving data management practices in the construction sector [10]. Identifying which data are required by different actors, how these data should be structured, and through which formats and exchange mechanisms they should be delivered can support the development of more effective and interoperable information frameworks. These are essential for enabling digital tools to provide practical value for industry professionals and for supporting the implementation of sustainability and lifecycle-oriented strategies [11, 12].

Within this context, the paper investigates the data and needs of key stakeholders involved in the construction sector in relation to four selected topics: energy efficiency, sustainability, circularity and resource efficiency. The study focuses on answering the following research questions: *RQ1) What are the data needs of stakeholders in the construction sector in relation to energy efficiency, sustainability, circularity, and resource efficiency?; RQ2) Which formats and delivery methods are most commonly used by stakeholders in the construction sector to share this information?*

The study is based on a mixed-method research approach combining an online survey and targeted interviews conducted among stakeholders of the European construction sector.

The results provide insights into stakeholder data needs, preferred information formats, and current practices for information exchange. These findings contribute to supporting the development of more structured and interoperable information workflows capable of improving data accessibility and facilitating the implementation of sustainable practices in the built environment.

The work has been conducted within the EU research project "INTElligent digital tools for Green Renovation, Assessment, Transformation, Efficiency and Sustainability" (INTEGRATES), funded under the Horizon Europe programme. The INTEGRATES core goal is to develop a framework integrating Building Information Modelling (BIM), digital twins, and data services supported by neuro-symbolic AI, and in this context, the manuscript presents the first results of the activities aimed at identifying the key stakeholders involved across the building lifecycle (construction, renovation, operation, and end-of-life) and mapping their roles and responsibilities in relation to energy efficiency, sustainability, circularity, and resource efficiency objectives.

2 Methodology

The study has been structured using a mixed-method approach to answer the RQs, combining quantitative and qualitative data collection techniques.

The quantitative technique is based on an online survey, that aimed to collect structured information on stakeholder roles, data needs, and current information exchange practices within the construction sector. The qualitative technique, instead, consisted of targeted semi-structured interviews, conducted with selected stakeholders to further explore and contextualize the results obtained from the survey.

The collected data from both the survey and interviews have been analyzed using data mining techniques and subsequently represented through graphical visualizations to identify recurring patterns, differences among stakeholder groups, and key trends in information exchange practices.

2.1 Survey Structure

The survey has been structured into five sections: an introductory section and four thematic ones, each dedicated to one of the selected topics. The introductory section aimed to cluster the respondents according to their stakeholder profile and the EU countries in which they carry out their work.

The thematic sections follow the same structure, and they are divided into four subsections corresponding to four scenarios representing different stages of the building lifecycle: (i) new construction, (ii) renovation, (iii) district-scale development, and (iv) demolition. Each subsection includes the same set of questions to ensure consistency in the collected data and facilitate comparison across topics and scenarios. Table 1 presents the list of questions related to the energy efficiency topic and the new construction scenario, which are representative of the structure adopted for all topics and scenarios.

The survey has been translated into 9 languages to maximize participation and shared through mailing lists and professional networks of the INTEGRATES project partners, promoted via professional communication channels, and presented during events and meetings of the construction sector.

Table 1. List of survey questions for the "Energy Efficiency – New Construction" combination.

Section: Energy Efficiency – Subsection: New construction	
Q1	Do you usually work, or have you ever worked, on the construction of a new building?
Q2	Referring to the construction of a new building, which are the stakeholders among with you share data about the energy efficiency framework?
Q3	Which are your data needs about energy efficiency framework?
Q4	In which format do you share information with them?
	F1) Worksheet; F2) Document; F3) PDF file; F4) Images; F5) 2D model; F6) 3D model; F7) BIM format; F8) Simulation software; F9) Web application; F10) Dashboard
Q5	Which delivery methods do you use to share with them?
	M1) Physical media; M2) Email attachments; M3) Common Data Environment (CDE); M4) Company file servers; M5) Cloud storage; M6) Online dashboard; M7) Web application; M8) BIM server; M9) Digital twin platform

2.2 Interviews Structure

The interviews have been designed as a follow-up phase to the survey, maintaining a similar thematic structure while introducing additional questions (Table 2). An interview guide has been developed based on a preliminary analysis of the survey results and on the main uncertainties that emerged from the responses, to clarify ambiguous aspects and explore specific topics relevant to answering the RQs of the study.

Table 2. List of the additional questions asked during the interviews.

Additional questions	
Q1	How do you evaluate the integration and interoperability level of your information system? Where do you see opportunities for improvements?
Q2	How would you describe the construction/renovation/operation/demolition workflow in terms of 3–5 main steps from your perspective?
Q3	What are the best critical decision points in this workflow to optimize processes?

Interviewees have been identified both through the project consortium partners and among survey respondents who indicated their availability to be contacted for a follow-up interview. A subset of participants has been then selected to ensure a reasonable representation of different stakeholder profiles. Interview transcripts and notes have been qualitatively analyzed through thematic coding. The analysis focused on identifying recurring themes related to interoperability challenges, information continuity, data duplication, and digital workflow integration.

3 Results and Discussion

This section presents the main findings of the study regarding stakeholder information needs and current practices for data exchange within the construction sector. Firstly, the results obtained from the online survey are presented, and secondly, the main insights emerging from the stakeholder interviews are discussed.

The dissemination of the survey through different platforms and communication channels enabled the collection of 101 responses from stakeholders operating within the EU construction sector. Respondents represent a wide range of professional roles involved across different phases of the building lifecycle, with engineers that constitute the largest group of participants (33 respondents), followed by architects (14), contractors or construction companies (14), and material suppliers or industrial companies (14). Additional respondents include facility managers (11), energy consultants (9), and regulators (6). This distribution highlights the presence of actors engaged along the entire value chain (design, construction, operation, and regulatory activities), providing more holistic results of the survey. Considering the geographical distribution, most respondents operate in Italy (35%), followed by Belgium (11%), Greece (9%), Bulgaria and Germany (8% each). The remaining responses are distributed across other European countries, confirming the international scale of the survey.

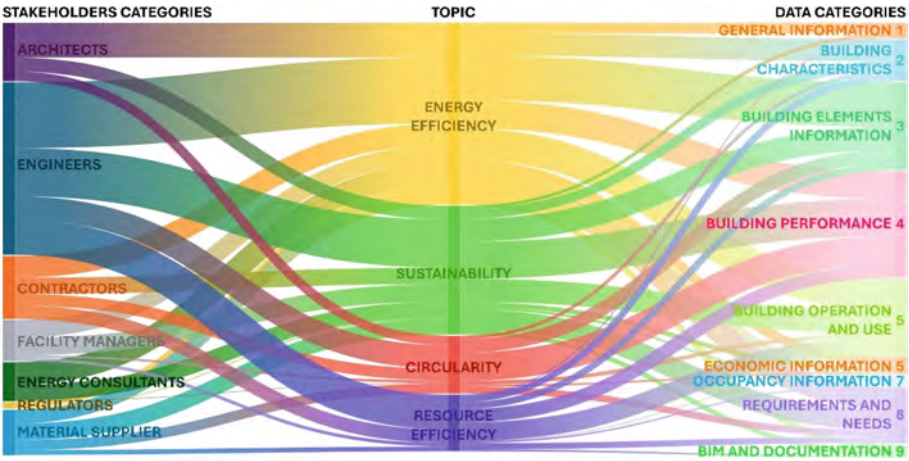


Fig. 1. Sankey diagram illustrating the relationships between stakeholder categories, thematic topics, and the corresponding data categories identified in the survey.

Figure 1 presents the results of Q3 of the survey and contributes to addressing the RQ1 of the study, which investigates the types of data required by stakeholders in the construction sector. The data has been categorized using the information groups commonly included in DBLs and DPPs, ensuring consistency with existing frameworks and practices already adopted in the sector.

The results highlight that all four topics are strongly connected to several data categories, particularly “Building performance”, “Building elements information”, and

"Building operation and use". Each of these categories contributes at least 17% of the responses for all four topics, highlighting that stakeholders require both performance indicators and detailed technical information about building components. Another relevant category is "Requirements and needs", which represents between 11% and 16% of the responses. This highlights the importance for stakeholders of accessing information capable of supporting decision-making processes, regulatory compliance, and the identification of performance targets throughout the building lifecycle.

Figure 2 presents the results of Q4 and Q5 of the survey and contributes to addressing RQ2 of the study, which aims to identify the most common formats and delivery methods used for information exchange among stakeholders in the construction sector. The results show that document-based formats remain the dominant approach for information exchange. In particular, PDF files (F3) represent the most widely used format across all stakeholder categories, accounting for 88% of the responses. This is followed by worksheets (F1) and documents (F2), which account for 62% and 58% of responses, respectively. These formats are consistently adopted across most stakeholder categories, suggesting that information exchange in the sector still relies heavily on traditional document-based practices. In contrast, more advanced digital formats such as simulation software (F8), web applications (F9), and dashboards (F10) show significantly lower usage levels, below 20% of responses. This suggests that, although digital and model-based approaches are increasingly promoted within the construction sector, their adoption for daily information exchange is still relatively limited.

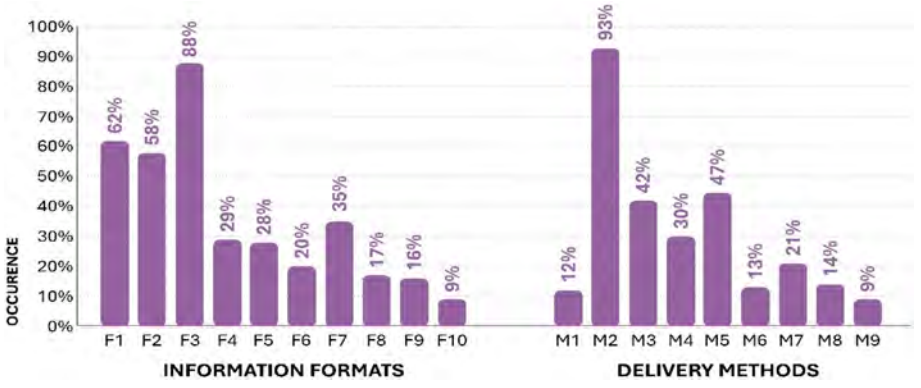


Fig. 2. Distribution of information formats (F1–F10) and delivery methods (M1–M9) used by stakeholders of the construction sector for sharing information.

A similar pattern emerges when analysing the delivery methods used to share information. The results clearly show the predominance of email attachments (M2), which are used by 93% of respondents, making them by far the most common delivery method across all stakeholder categories. Other digital infrastructures, such as cloud storage services (M5) and common data environments (M3), show moderate levels of adoption (47% and 42% respectively), indicating that shared digital environments are increasingly used to support collaboration and data exchange.

Other delivery methods appear to play a more complementary role. Company file servers (M4) and online dashboards (M6) are used by 29% and 13% of respondents, respectively, while more advanced solutions such as web applications (M7), BIM server (M8), and digital twin platforms (M9) show limited adoption across the surveyed stakeholders. Traditional approaches such as physical media (M1) also appear marginal, accounting for only 12% of responses.

The interviews have been conducted with stakeholders representing different roles within the construction sector, to manage a deeper interpretation of the survey results and provide additional context regarding current practices and challenges related to information management and exchange across the building lifecycle. A total of 13 interviews have been performed for the study.

A recurring theme emerging from the interviews concerns the fragmentation of information workflows and the limited interoperability between software environments used by different stakeholders. Several participants highlighted that information exchange often relies on manual transfers or static document formats, even when digital modelling tools are internally adopted.

Another frequent issue concerns the discontinuity of information across lifecycle phases. Interviewees reported that information generated during early project stages is frequently not transferred in a structured way to facility managers or demolition stakeholders, limiting the possibility of reusing data for maintenance, renovation, or circularity-related assessments.

Interestingly, several interviewees reported that advanced digital tools such as BIM platforms or simulation environments are increasingly adopted within specific organizational workflows, while information exchange between organizations still predominantly occurs through static and non-interoperable formats. This suggests that the gap is not only technological but also organizational and procedural.

The findings suggest that the main barrier to digital information exchange in the construction sector is not necessarily the absence of digital tools, but rather the lack of shared and interoperable workflows connecting stakeholders across lifecycle phases. While BIM-based and platform-oriented approaches are increasingly available, their use for inter-organizational information exchange remains limited. This indicates that the transition toward lifecycle-oriented digital ecosystems, such as DBLs and DPPs, requires not only technological adoption but also clearer information governance structures and standardized data exchange practices.

4 Conclusion

This study explored the information needs and data exchange practices of stakeholders operating within the European construction sector in relation to four key topics: energy efficiency, sustainability, circularity, and resource efficiency. The study shows that the construction sector is currently positioned in a transitional phase between traditional document-based information exchange practices and more integrated digital workflows. Although digital tools are increasingly available within organizations, information exchange across stakeholders and lifecycle phases still largely depends on static formats and fragmented delivery methods. By systematically mapping stakeholder information

needs in relation to the four topics, the study contributes to identifying the information gaps and interoperability challenges that may hinder the implementation of lifecycle-oriented digital frameworks. The results highlight the importance of developing shared data structures, interoperable exchange mechanisms, and governance approaches capable of ensuring information continuity throughout the building lifecycle. These aspects appear particularly relevant for supporting circular economy strategies, renovation processes, and long-term building performance monitoring. Future research should further investigate how stakeholder-specific information requirements can be translated into standardized digital data models and operational workflows supporting cross-phase collaboration in the built environment.

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Legal Risks and Liability in the Use of Artificial Intelligence for the Design, Planning and Management of Sustainable Buildings

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Abstract. Artificial intelligence (AI) is increasingly integrated into the design, planning, and management of sustainable buildings, supporting decisions related to energy performance, material circularity, environmental compliance, and structural safety. This paper examines, from a legal and civil liability perspective, the risks arising from the use of AI-based tools and online advisory systems in construction-related processes. The main objectives are to identify liability gaps, analyse the effects of algorithmic opacity on the assessment of fault and causation, and clarify the responsibilities of professionals and digital service providers. The methodology combines doctrinal legal analysis, a comparative evaluation of emerging regulatory frameworks, and scenario-based assessments relevant to sustainable construction workflows. The findings reveal significant vulnerabilities in establishing professional fault, defining the standard of care, ensuring data accuracy, and allocating liability among designers, engineers, beneficiaries, digital platform operators, and AI developers. Particular attention is given to risks associated with automated decision-making and the reliance on AI-generated technical or legal recommendations. The contribution of the paper consists in proposing a Hybrid Accountability Model integrating updated civil liability rules, algorithmic transparency obligations, contractual allocation mechanisms, and reinforced professional standards. The relevance to the conference themes lies in ensuring that AI-enabled sustainable construction practices evolve within a clear, accountable, and ethically robust legal framework.

Keywords: Civil liability · Artificial intelligence · Sustainable construction · Algorithmic opacity · BIM traceability

1 Introduction

Integrating artificial intelligence (AI) into sustainable building design, planning, and management creates an acute evidentiary challenge: fragmented decision traceability. Probabilistic outputs and "black-box" processing hinder the direct reconstruction of the causal chain—namely, identifying determinant parameters, proving human validations, and locating error propagation. Consequently, assessing professional fault and causation

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becomes uncertain, often shifting liability among designers, verifiers, clients, and digital actors. When AI influences structural or compliance decisions, this evidentiary opacity threatens infrastructure safety itself.

General civil liability law, founded on the individual imputability of a wrongful act, inadequately addresses these scenarios. In AI-assisted workflows, the core issue is not the mere use of the tool, but the ability to establish, *ex post*, who decided, on what basis, within what constraints, and following what verifications. Without verifiable traceability, analysing fault, causation, and civil liability becomes inherently unstable.

This paper pursues three objectives: (1) identifying liability vulnerabilities in AI-assisted construction; (2) analysing how algorithmic opacity affects proving the fault–causation–damage triad; and (3) clarifying duties under the new EU regulatory framework. Key contributions include a legal risk taxonomy for seven AI use typologies (Table 1), an updated standard of care based on verifiable oversight, and a Hybrid Accountability Model (HAM) grounded in functional traceability (Table 2).

2 AI Workflows in Sustainable Construction and Risk Taxonomy

In sustainable projects, AI operates as decision support or an automation factor throughout design, execution, and operation. From a legal perspective, the critical juncture occurs when the algorithmic output becomes determinant for a technical decision. Particularly upon uncritical adoption, the absence of evidentiary links (data provenance, algorithm versions, decision logs) directly compromises the parties' standing in civil litigation [2, 12, 13].

To avoid a purely abstract evaluation, this paper proposes a taxonomy of seven recurrent AI use typologies (U1–U7), synthesised in Table 1. This framework correlates each construction stage with the dominant legal risk and the minimum traceability pack required for evidence. The analysis demonstrates that vulnerabilities systematically converge on three factors: data quality, output traceability, and human validation documentation. Among these, three critical scenarios (S1–S3) will ground the subsequent analysis. The table's examples are strictly illustrative, relying on public sources, without implying actual incidents within those projects.

Table 1. AI use typologies in sustainable construction and associated legal risks (U1–U7)

Typology (code; stage; output)	Legal risk vector	Minimum traceability pack
U1 (Design) *energy optim.* ***(e.g., Powerhouse)*** [1]	data/assumption error → performance gap	inputs + assumptions; model/v; report
U2/S1 (Design) *generative/topology* ***(e.g., Generative design)*** [13]	black-box in safety choices; weak verification	constraints log; tool version; independent verification
U3/S3 (Design) *low-carbon materials* ***(e.g., EC3)*** [3]	data provenance/recency; incompatibility	EPD/LCA version; validity window; selection record

(*continued*)

Table 1. (*continued*)

Typology (code; stage; output)	Legal risk vector	Minimum traceability pack
U4/S2 (Permit) *automated compliance* ***(e.g., e-Adeies)*** [4]	false compliance; reliance; rule drift	rule-set version; run log; BIM snapshot
U5 (Constr.) *robotic/3D print* ***(e.g., MX3D)*** [5]	latent defect; split causation	execution + calib. log; QC trace
U6 (Oper.) *digital twin* ***(e.g., MX3D)*** [5]	automation without guardrails; weak warnings	thresholds; alert/command log; interventions
U7 (Cross) *AI advisory* ***(e.g., UpCodes)*** [6]	reliance; weak caveats; standard-of-care ambiguity	prompt/response; disclaimer; human review note

3 Methodology and Analytical Lens

The methodology combines three complementary layers. The first entails a doctrinal analysis of civil liability rules to identify junctures where the absence of decision traceability undermines the proof of fault and causation. The second maps the new European Union regulatory framework (AI Act and PLD 2024) to evaluate whether emerging transparency obligations can remedy these evidentiary gaps.

The third layer comprises a scenario-based assessment. Functioning as a doctrinal-analytical testing tool for recurrent industry situations, it examines three critical scenarios selected from the proposed taxonomy (Table 1): generative design in safety choices (S1), digital compliance screening (S2), and low-carbon material selection (S3).

Because professional liability standards are jurisdiction-dependent, the scenarios are not presented as universal fault rules. Civil law systems usually structure the inquiry around statutory duties, professional obligations, unlawfulness, fault, causation and damage, whereas common law systems frame it through duty of care, breach, foreseeability and negligence. HAM therefore has an evidentiary, not harmonising, function: it helps reconstruct AI-assisted decisions under the applicable legal system.

For each scenario, the analysis follows a strict protocol guided by the traceability chain of AI-assisted decisions (Fig. 1), moving from data provenance and AI model logic to output generation, professional validation, decision sign-off, implementation and effect. Within this chain, the main evidentiary gaps are identified as follows: G1 concerns data provenance, including the quality and validation of input data; G2 concerns model opacity and the limited explainability of the system's internal logic; G3 concerns documented supervision of the generated output and the scope of what was actually reviewed; G4 concerns decision traceability, namely whether the professional sign-off can be linked to an identifiable factual and technical basis; and G5 concerns the causal link in implementation, including handover, site execution or operational deployment. The assessment then proceeds in three steps: (i) identifying the generated output; (ii) locating the evidentiary gap within the chain; and (iii) evaluating how algorithmic opacity affects the standard of care and liability allocation.

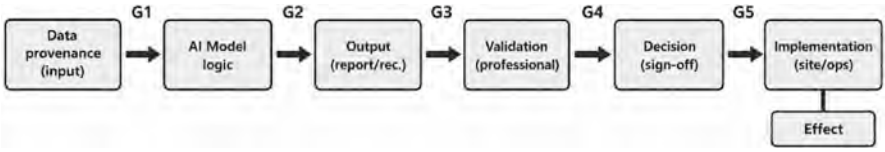


Fig. 1. Traceability chain in AI-assisted construction decisions

4 EU Regulatory Framework for AI in Construction

The European Union's regulatory framework does not establish a unitary civil regime for AI, but acts cumulatively to shape the standard of professional care and decision transparency [16].

On the one hand, Regulation (EU) 2024/1689 (AI Act) [7] configures obligations proportional to system risk and delimits actor responsibilities, particularly between providers and deployers. Where an AI system qualifies as high-risk, including where it operates as a safety component or falls within covered infrastructure-related uses, the Act imposes requirements that are directly relevant to construction practice: data governance, technical documentation, logging, transparency and human oversight. Even outside the strict high-risk category, targeted transparency duties for certain AI systems may indirectly influence professional expectations in technical and compliance-sensitive environments.

On the other hand, Directive (EU) 2024/2853 [8] reforms the evidentiary regime, remaining the primary applicable European civil instrument following the withdrawal of the proposed AI Liability Directive (AILD) [9, 17]. The explicit classification of software as a "product" (Art. 4) and the establishment of rebuttable presumptions regarding causation and defectiveness (Art. 10) provide courts with legal mechanisms to mitigate the information asymmetry inherent in opaque systems [8].

Within this ecosystem governed by defective product liability and common national law, BIM standardisation (ISO 19650-2:2018) [10] serves as an auxiliary technical benchmark, supplying the terminology and procedures necessary to objectively and contractually version these techno-legal requirements.

5 Liability Gaps Under Algorithmic Opacity

Table 1 and scenarios S1–S3 show that the central legal risk of AI lies in its effect on evidence. Digital decisions result from a chain of data, algorithms and validations. When that chain is untraceable, disputes shift from technical error to governance error, weakening the assessment of fault and causation.

Fault: From Calculation Errors to Verifiable Omissions. In professional liability, fault is assessed against the conduct of a prudent professional in similar circumstances. In AI-assisted workflows, opacity shifts the standard toward verifiable oversight. Fault is often evidenced by procedural omissions: inadequate data, incomplete constraints, lack

of independent validation or automation bias [2, 13]. In S1–S3, this appears respectively as structural-constraint error, automation bias and data-governance negligence.

Romania's framework under Law No. 10/1995 [11] illustrates this point: construction quality depends on personal assumption of responsibility. Formal approval of an AI output without logs or validation reports may turn technical uncertainty into documentable negligence.

Causation: traceability breaks in multi-actor chains. In the AI context, the practical difficulty is not causation theory, but the break in traceability. Without logs, identifying the determinant deviation becomes difficult and responsibility disperses across the multi-actor chain. S1 breaks the link between the optimised model and real safety conditions; S2 fragments causation between digital workflow and human validation; S3 shifts the dispute to data defect versus model defect.

In systems such as Greece's e-Adeies platform [4], formal digital traceability may create a risk that procedural compliance is confused with substantive professional validation. In seismically vulnerable environments, the absence of technical traceability may make liability allocation highly uncertain.

Standard of Care: Verified and Documented Oversight. The standard of care cannot be formulated as either an obligation to avoid AI or the automatic acceptance of its output. The operational formula becomes exercising verified and documented oversight over tool integration. This requires: (1) defining safety constraints; (2) controlling data; (3) independently validating the output; and (4) archiving decision artifacts. Scenario applications demand hard constraint verification and structural cross-checks (S1), essential *sanity checks* (S2), and traceable data governance (S3).

Without traceability, signatures become formalities and evidentiary boundaries between professionals and digital actors remain unstable, creating a liability debt that requires a hybrid model.

6 A Hybrid Accountability Model for AI-Assisted Sustainable Construction

Analysis demonstrates that abstract civil liability rules are insufficient for decisions mediated by opaque systems. The primary difficulty lies not in algorithmic inexplicability, but in the absence of functional traceability sufficient to delineate contributions and evaluate professional care ex post. To address this, the paper proposes a Hybrid Accountability Model (HAM) articulated on three pillars.

6.1 Pillar 1: Minimum Verifiable Traceability—The AI-Use Logbook

HAM requires the capability to reconstruct technical decisions by establishing an AI-Use Logbook, natively correlated with BIM information management. This instrument must record five critical artifacts: (1) provenance and version of the data used; (2) identity and version of the digital tool; (3) matrix of imposed safety parameters and constraints; (4) generated output coupled with an independent verification summary; and (5) decision attestation. The logbook transforms liability from a theoretical attribution into a reconstructible reality.

Practically, the independent verification summary is not a generic sign-off: in S1, it would record the reviewed AI-generated topology, applicable structural benchmark, independent cross-check, detected deviation, accept/revise/reject decision and logbook ID linked to the BIM version.

6.2 Pillar 2: Contractual Allocation—A Model Clause for AI Use

The second pillar uses an explicit AI-use clause in design and execution contracts. The clause should confirm AI's decision-assistive role and regulate data cleaning, pre-assumption validation, software updates, incident-related evidence preservation and cooperation through log exports. In projects governed by standard international contracts, including FIDIC-based forms [18], it would operate as a project-specific layer through Particular Conditions, technical schedules or, where applicable, Employer's Requirements. It would not displace the existing allocation of responsibilities among employer, contractor, designer or engineer unless expressly agreed. Rather, it would make the procedural and evidentiary conditions of AI use auditable, complementing the standard contractual architecture and the BIM–legal interface [14, 15].

6.3 Pillar 3: Insurance and Risk Pooling Conditioned on Audit Readiness

Residual risks arising from data, software and human decision-making may be managed through professional liability insurance linked to audit readiness. A "no logbook, no coverage" heuristic would limit coverage where the minimum traceability pack is missing and discourage uncritical reliance on AI outputs.

Table 2. Responsibility matrix and minimum evidence artifacts for traceability

Actor (role cluster)	Minimum duties (standard of care)	Minimum evidence artifacts	Typical failure points
Design prof. (lead designer)	Set constraints; treat AI as input; require documented validation	Brief + constraints; BIM model vID; validation memo	Blind reliance; no version control
Safety-critical (structural)	Impose hard safety constraints; run independent checks	Constraint/parameter log; benchmark calculation; independent verification summary	Missing constraints; sign-off on summaries
Compliance (permit lead)	Verify rule-set scope/version; confirm inputs; document exceptions	Rule-set snapshot (v/date); run log; exception list	False compliance; rule drift
Delivery (contractor/QC)	Process control + calibration; QC; align as-built with model	Execution/calibration records; QC/sensor logs	Latent defects; undocumented deviations

(*continued*)

Table 2. (*continued*)

Actor (role cluster)	Minimum duties (standard of care)	Minimum evidence artifacts	Typical failure points
Operations (facility manager)	Set guardrails; review alerts; document interventions	Telemetry/thresholds; alert/command logs	No guardrails; ignored alerts
Digital supply chain (vendor)	Disclose limits + updates; provide audit export; data provenance	Tool version + changelog; logging spec; data provenance	Silent updates; no audit export

7 Conclusions and Practical Implications

This paper has demonstrated that adopting AI tools within the sustainable construction ecosystem is not merely a technological transition, but a distinct evidentiary and accountability challenge. The main deficiencies in establishing liability stem not from the inherent imperfection of algorithms, but from the difficulty of applying general civil liability rules to hybrid decisions, where the boundary between digital recommendation and human assumption becomes fluid. Faced with systemic opacity, civil courts may encounter significant difficulty in applying classical rules equitably, since fault and causation cannot be reliably evaluated within a documentary vacuum.

The central conclusion is the need for accountability-by-design: algorithmic decisions affecting safety or performance must remain attributable. Although the AI Act and PLD 2024 strengthen traceability and evidentiary expectations, their practical efficacy depends on project-level operationalisation. HAM responds to this need by offering courts a coherent evidentiary pack.

The practical recommendations resulting from the analysis target three convergent directions: (1) establishing a minimum standard of verifiable traceability for AI use, calibrated proportionally to the decision's risk; (2) synchronising the BIM–legal interface by integrating the *AI-Use Logbook* into native project workflows; and (3) consolidating contractual and insurance discipline through model clauses and coverage mechanisms conditioned on *audit readiness*, including measures for preserving digital evidence upon an incident.

Without a verifiable framework and transparent risk allocation, AI may generate a liability debt, paid through difficult litigation and erosion of trust in green projects. This outcome is not inevitable: through rules, practices and evidentiary tools, AI can be integrated into sustainable construction consistently with structural safety, professional ethics and legal predictability.

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From Climate Requirements to Practice - Waste Management Integration in the Design Phase of Construction Projects

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Abstract. This study examines how design–build contractors integrate waste management considerations into the design phase of construction projects in response to Denmark's climate requirements for Life Cycle Assessment (LCA) modules A4 (transport) and A5 (construction), effective from July 2025. The objective is to understand current practices, identify organisational and logistical barriers, and explore how early project planning can support improved resource efficiency and regulatory compliance. A qualitative research approach was applied based on six semi-structured interviews with professionals in Danish design–build construction organisations. Institutional theory served as the analytical framework for understanding how regulatory pressures influence organisational practices and decision-making processes. The findings indicate that waste management practices are strongly influenced by regulatory requirements related to climate reporting. While companies increasingly improve waste documentation and sorting practices during construction, integration of waste management into the design phase remains limited. Fragmented responsibilities across project phases, data reliability challenges, and logistical constraints on construction sites influence how waste management practices are implemented. The study also identifies emerging sustainability roles within construction organisations that support life-cycle assessment documentation and regulatory compliance. The study concludes that stronger integration of waste management considerations into the design phase, improved coordination among project actors, and more reliable environmental data systems are necessary to support compliance with climate regulations and enhance resource efficiency in construction projects.

Keywords: Climate requirements · Waste Management · Life Cycle Assessment · Construction waste · Design–Build Contracting

1 Introduction

The construction sector plays a significant role in global greenhouse gas emissions and resource consumption. In Denmark, the building industry accounts for approximately 30% of national greenhouse gas emissions, leading to increasingly strict environmental

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regulations [1]. In response, the Danish Building Regulations introduced mandatory life cycle assessments (LCAs) for buildings, requiring that emissions across a building's life cycle be documented and evaluated [2]. Recent regulatory updates have further strengthened these requirements. From July 2025, emissions from the construction process must be documented separately for modules A4 and A5 and must remain below 1.5 kg CO_2 e/m^2/year [3]. Module A4 includes transportation of materials and equipment to the construction site, while module A5 covers activities during the construction process itself, including energy use, material losses, and waste generation [4].

Construction waste plays a particularly important role in this context. Studies indicate that waste generation represents a substantial share of emissions associated with the construction phase of building projects [5]. Recent research has further emphasised the importance of integrating waste management practices throughout the construction lifecycle, particularly during the design phase, where decisions on materials and logistics influence the amount of waste generated during construction [10, 12].

In addition, circular economy principles increasingly emphasise the importance of resource efficiency and waste reduction within construction processes [13]. These perspectives highlight the need to improve the planning and management of waste streams throughout construction projects. Traditionally, waste management has been addressed mainly during the execution phase of construction projects. However, many of the decisions that influence waste generation occur earlier in the project lifecycle. Design decisions related to material selection, modular dimensions, prefabrication and construction logistics can significantly affect the amount of waste generated during construction.

Previous research highlights the importance of waste reduction and life-cycle assessment in construction [10, 12]. However, how design–build contractors integrate waste management into the design phase in response to climate requirements remains insufficiently understood. Design–build contractors are particularly relevant actors in this context because they are responsible for both design and construction phases of projects. This creates opportunities to integrate waste management considerations earlier in project planning. Based on this context, the study addresses the following research question:

How do design–build contractors integrate waste management into the design phase in response to Denmark's climate requirements for LCA modules A4 and A5?

2 Theoretical Framework

2.1 Institutional Theory

Institutional theory explains how organisations adapt practices in response to external pressures such as regulations, professional norms, and industry expectations [6, 7]. According to DiMaggio and Powell [6], organisations tend to become increasingly similar over time through institutional pressures, including regulatory, normative, and mimetic pressures. Regulatory pressures arise from laws and policies, normative pressures from professional standards and education, and mimetic pressures from organisations imitating industry practices.

Institutional theory has frequently been applied to explain sustainability transitions in industries facing increased environmental regulation [7]. In the construction sector, the

Danish climate requirements for modules A4 and A5 represent strong regulatory pressure, requiring companies to document emissions from transport, energy use, and waste generation during construction projects. The theory provides a useful framework for understanding how construction companies adapt waste management and environmental documentation practices in response to climate regulations.

3 Methodology

This study applies a qualitative research methodology based on six semi-structured interviews with professionals from Danish construction companies involved in design–build projects. The aim was to explore organisational practices and experiences related to waste management and environmental documentation in construction projects. Respondents were selected through purposive sampling to ensure they had direct experience with waste management practices, construction project management, and life-cycle assessment (LCA) documentation. Participants represented a range of professional roles, including sustainability consultants, project managers, and construction leaders. These professional roles were selected because they are directly involved in project planning, construction management, and environmental reporting.

Semi-structured interviews allow respondents to describe their experiences and perspectives while ensuring that key topics are addressed systematically [8]. The interview guide was developed based on the research question and the theoretical framework of institutional theory. The questions focused on four main themes: waste management practices, organisational responsibilities, regulatory requirements, and challenges associated with LCA documentation.

The interviews primarily used open-ended questions to encourage respondents to elaborate on their experiences and organisational practices. Follow-up questions and prompts were used when necessary to explore emerging themes further and clarify specific examples. Although some flexibility was allowed regarding the depth of responses, all interviews followed a consistent thematic structure to ensure comparability across respondents. The interviews were conducted both online and in person between September and December 2025, recorded with the respondents' consent, and subsequently transcribed.

The data were analysed using thematic coding to identify recurring patterns in waste management practices, organisational structures, regulatory pressures, and LCA challenges. The identified themes were subsequently grouped into broader analytical categories aligned with the research question and institutional theory framework. Although the sample size is limited, qualitative interviews provide valuable insights into organisational practices and industry perspectives [9]. Due to article length constraints, only the main interview themes and analytical procedures are presented in this paper rather than the complete interview guide and full coding framework.

4 Results

The thematic analysis identified four themes related to integrating waste management practices in construction projects, illustrating how construction companies currently address waste management in response to regulatory requirements.

4.1 Regulatory Pressure as a Driver of Change

Across the interviews, regulatory requirements emerged as the primary driver of change and increased attention to waste management. The introduction of CO_2 limits for modules A4 and A5 requires construction companies to document waste streams and transport emissions more systematically.

Several respondents stressed that waste management has become increasingly relevant because it significantly affects climate calculations during construction. One respondent emphasised the importance of waste in climate calculations:

> *"Waste is one of the biggest contributors to A5 emissions. If waste fractions are not documented properly, the CO_2 result can be significantly worse." (Interview 6)*

Respondents therefore perceived the new regulatory requirements as a key factor motivating companies to improve their waste management practices. The need to document emissions related to transportation, material use, and waste generation forces companies to track waste flows more systematically than before.

Several respondents emphasised the need for economic incentives to improve waste management. Construction waste represents both material loss and additional disposal costs. Reducing waste quantities can therefore generate financial benefits for construction companies. One respondent described this relationship between sustainability and cost efficiency:

> *"There is a large waste of resources in construction. If we can reduce the amount of waste and sort it properly, it saves both materials and money." (Interview 4)*

Despite increased awareness, most respondents indicated that waste management still receives most attention during the construction phase rather than during the early design phase. However, interviews also revealed that regulatory requirements have not yet led to a systematic integration of waste considerations in the design phase.

4.2 Organisational Responsibilities and Project Structures

Another theme concerns the distribution of responsibilities for waste management within construction projects. The interviews indicate that responsibility for waste management is primarily located within the construction phase and is typically managed by site managers. Subcontractors are responsible for following the waste-sorting procedures defined by the main contractor, while waste transport companies collect the waste and provide documentation of waste fractions.

Several respondents also indicated that responsibilities related to waste management during the design phase remain less clearly defined. Although sustainability departments or environmental specialists may support project teams with life-cycle assessment calculations, integrating waste planning into early project stages is not always systematically addressed. In some cases, design decisions are made without detailed consideration of how materials will be handled during construction or how waste streams will be documented.

"Waste sorting is something that mainly gets attention during construction. It depends very much on the site management." (Interview 3)

However, a few respondents noted that their companies have begun involving sustainability specialists earlier in project planning to improve documentation and compliance with regulatory climate requirements.

4.3 Practical Implementation Barriers

Several practical barriers to implementing waste management were identified. One challenge concerns the availability and reliability of waste data. Construction companies often rely on external waste transport companies to provide documentation of waste quantities and fractions. Respondents explained that this reliance can create uncertainties in the data used for life-cycle assessments. Inaccurate or incomplete waste data can significantly affect the calculated emissions associated with construction activities. Several respondents therefore emphasised the importance of improving data transparency across the construction supply chain.

Another barrier relates to logistical constraints on construction sites. Respondents explained that the physical characteristics of construction sites can affect the implementation of efficient waste-sorting systems. Limited space, particularly in dense urban areas, can make it difficult to establish multiple waste-sorting containers and efficient sorting systems. One respondent described this situation:

"If waste sorting is not considered early in the project, there may not be enough space for the containers on the site." (Interview 4)

Respondents highlighted challenges with waste classification and the emissions factors in LCAs. Mixed waste fractions can be difficult to classify accurately, and the environmental impact associated with different waste types is sometimes uncertain.

4.4 Organisational Learning and Sector Development

The interviews identified initiatives to improve waste management practices within construction organisations. Respondents emphasised the importance of cultural change within construction organisations. Several respondents explained that their companies have begun implementing initiatives to improve waste management practices, strengthen worker awareness, and increase sorting accuracy on construction sites. These initiatives often include onboarding training programs for workers, visual sorting guides on construction sites, and information campaigns to raise awareness of waste management procedures.

Several respondents reported that digital tools are increasingly used to support waste documentation and environmental reporting. These tools include BIM-based project management systems, digital waste-tracking platforms, and LCA software for documenting material flows and construction-site emissions. Some companies have introduced digital dashboards that allow project teams to monitor waste data in real time, aiming to improve awareness and sorting accuracy on construction sites. However, respondents

emphasised that organisational change in the construction sector takes time, as projects involve multiple actors and established routines that make it difficult to implement new practices quickly.

5 Discussion

The findings of this study highlight how the Danish climate requirements for LCA modules A4 and A5 are increasingly shaping environmental practices within the construction sector. The introduction of separate climate requirements for construction-related emissions appears to have strengthened organisational attention towards waste documentation, waste sorting, and environmental reporting during construction projects. Several respondents also linked improved waste management to both environmental performance and economic efficiency, suggesting that waste reduction is increasingly viewed as both a sustainability and resource management issue. The study further indicates that construction companies are gradually adapting their organisational practices in response to increased environmental requirements. The growing involvement of sustainability specialists and the use of BIM-based project management systems, digital waste-tracking platforms, and LCA software indicate that environmental management is becoming more integrated into project coordination and organisational routines. Similar developments have also been identified in previous studies on environmental regulations and construction management practices [10, 11].

However, the findings indicate that waste management considerations are primarily addressed during the construction phase rather than systematically integrated into early project planning and design. Respondents described how waste management responsibilities are often concentrated at the construction site level, while early design decisions regarding materials and logistics are less closely tied to waste prevention strategies. This supports previous research suggesting that waste reduction measures are often implemented too late in the project lifecycle [10, 12]. The findings further indicate that fragmented responsibilities may create barriers to integrating waste prevention into early decision-making processes. Construction projects involve multiple actors with different responsibilities in design, planning, construction, and environmental documentation, which may reduce coordination across project phases. Earlier collaboration between design teams, contractors, and sustainability specialists may therefore support more resource-efficient construction practices and strengthen the integration of waste management into project planning.

Another important implication concerns the reliability of environmental data used for life-cycle assessments. Several respondents explained that construction companies depend on subcontractors and waste transport companies for waste documentation and reporting. This dependency may create uncertainty regarding waste quantities and environmental calculations. Similar challenges related to environmental data quality and transparency have also been identified in previous research [11]. Improving coordination and standardising documentation procedures across the construction supply chain may therefore strengthen the reliability of environmental assessments and support compliance with climate regulations.

Overall, the findings suggest that the construction sector is gradually adapting to increased environmental requirements, although the integration of waste management

into the design phase remains limited. Achieving stronger integration may require clearer organisational responsibilities, improved collaboration among project actors, and earlier consideration of waste management during project planning and design. In addition, the findings indicate that regulatory requirements alone may not be sufficient to ensure organisational change unless environmental considerations are systematically embedded into project coordination and decision-making processes.

6 Conclusion

This study examined how design–build contractors integrate waste sorting into the design phase in response to Denmark's climate requirements for life cycle assessment (LCA) modules A4 and A5. The findings indicate that waste management practices in construction projects are strongly influenced by regulatory pressures related to climate requirements. These regulations encourage construction companies to strengthen waste documentation and sorting procedures. However, waste management is still primarily addressed during the construction phase rather than systematically integrated into early design activities. Fragmented responsibilities across project phases, uncertainties related to waste data, and logistical constraints on construction sites influence how waste management practices are implemented. The emergence of sustainability roles within construction organisations also suggests that environmental considerations are gradually becoming more embedded in project planning processes.

Improving waste management practices may require stronger integration of environmental considerations into early project planning, clearer organisational responsibilities across project phases, and more reliable systems for documenting construction waste. Future research could examine construction projects and organisations to identify best practices for waste management in the design phase. The study contributes to understanding how regulatory climate requirements influence organisational practices and waste management integration in design–build construction projects.

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Implementation of Sustainability Reporting Standards: Readiness of Joint Stock Companies from Serbia vs. North Macedonia

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Abstract. The commitment of companies to Environmental, Social, and Governance (ESG) issues has never been more relevant or emphasized in the global socio-economic environment. The aim of the paper is to make a comparative analysis of ESG reporting in the Republic of Serbia (RS) and Republic of North Macedonia (RNM), starting with the legal and regulatory framework and afterwards with practical implementation of the ESG reporting by joint stock companies listed on Serbian (index BELEX15) and Macedonian (index MBI10) stock exchanges, respectively. The study uses a mixed-methods design that integrates both qualitative and quantitative techniques. The qualitative part consists of gathering and analyzing legal and regulatory acts, and reports published by analyzed joint stock companies. The quantitative analysis includes evaluating and scoring indicators according to ESG segments of the reports. The results show the level of maturity of Serbian and Macedonian companies of implementing ESG standards in their operation by statistical and visual presentation of the findings by using Microsoft Excel. Companies listed in MBI10 demonstrate a good ESG maturity level, whereas companies listed in the BELEX15 show moderate ESG maturity level. Considering the research results, the paper provides recommendations for improving ESG reporting practices in Serbia and North Macedonia.

Keywords: ESG · sustainability reporting · corporate governance · joint-stock companies · regulatory compliance

1 Introduction

Integrating ESG issues into investment decisions is more common nowadays. According to IFC (2021) the strategic commitment of a company to ESG issues and performances has been recognized by investors and financial markets. ESG ratings and data have become a crucial foundation for responsible investing, empowering the investors with upgraded and broadened data, including environmental, social and corporate governance data, that is unavailable in financial statements of the companies. ESG reporting should overcome the information asymmetry between different market participants, such as

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investors and other stakeholders. The E aspects of ESG reflect the environmental issues including waste, use of (renewable) resources, GHG emissions, environmental policies etc. The S aspect of ESG includes social dimension of companies' operation especially labor relations, occupational safety and health management system, diversity and inclusion, while G aspect emphasizes internal system of practices, law compliance and external stakeholders' relations (Henisz, Koller, & Nuttall, 2019). Sustainability or ESG reporting should provide to investors and other stakeholders the information how value has been created in the company, how employees and all the people in supply chains have been treated, have inclusivity and equality been promoted, how companies identify non-financial risks, how different risks have been managed, etc.

When analyzing the factors that affect the level of ESG disclosure (Helfaya, et al., 2023) came to the conclusion that sustainability reporting guidelines and national policies adjusted to cultural dimensions positively influence ESG practices and help mitigate country-specific weaknesses. Krambia-Kapardis et al. (2023) in their research emphasize that the regulation of ESG disclosure by governmental decree would be more productive than self-regulation by professional bodies or the Stock Exchange. Regarding the economic, historical, geopolitical similarities and relations between the countries, also and their status of candidates for EU membership, but taking into consideration the differences between countries in the way that ESG reporting is regulated, the analysis provides a conclusion about the ESG maturity of companies listed in the national stock indexes.

1.1 Compliance to the ESG Regulative Framework in the Republic of Serbia (RS)

According to the latest Serbian Law on Accounting (2019) all domestic companies classified as large legal entities (more than 500 employees) are required to publish non-financial reports as part of their annual reports. These reports contain information about sustainability and ESG issues, but there are no standardized form and obligatory content regarding these issues. Although sustainability reporting is obligatory only for large companies, and absence of universally accepted standards, guidelines, and instructions (Jovanović, 2025), awareness of other companies in terms of advantages of implementing ESG issues in the strategic orientation, and long-term benefits of commitment to the sustainability, through the prism of a company, consumers, social community, environment, protection of workforce rights, etc., has been slightly increased. But, the most expressed obstacles which slow the transition process towards long term sustainable business, especially for SMEs, are: lack of finance, and complexity of ESG reporting that requires employees with the ESG expertise. Companies from Serbia that export to the EU or participate in the supply chain of some EU companies, or some EU investors and banks invest in Serbian companies, are indirectly forced to disclose implementation of ESG factors in their business through the ESG reporting, by applying some of the international reporting standards (Global Reporting Initiative - GRI, IFRS ISSB) and some of directives and regulatory frameworks especially required in the EU, such as CSRD - Corporate Sustainability Reporting Directive, EU Taxonomy for Sustainable Activities, but also VSME - Voluntary Standard for non-listed SMEs set by EFRAG (The European Financial Reporting Advisory Group with the support of the European

Commission). That pressure of the EU market might be considered a stimulating factor for Serbian companies to embed ESG issues in the company's strategy and organizational culture.

1.2 Compliance to the ESG Regulative Framework in the Republic of North Macedonia (RNM)

The ESG reporting legal framework in the Republic of North Macedonia (RNM) is in its initial stage of development. The pioneer step toward increasing ESG awareness was taken when the requirement for listed joint-stock companies in RNM to include a corporate governance statement in their annual reports was incorporated into national law through the 2020 amendments to the Law on Trade Companies. In 2021, Macedonian Stock Exchange (MSE) introduced the Corporate Governance Code (CGC) as a soft-law instrument to strengthen governance standards and enhance stakeholder confidence in the securities market (MSE and SEC, 2021). The commitment for promoting sustainable investment and improving ESG oriented business aligned with best international practices, results with adoption of ESG reporting guideline, by MSE. The ESG disclosure in RNM is not mandatory for companies listed on the MSE, and is still based on the company's willingness to fill in and publish ESG reports no matter as a part of annual report, sustainability report or integrated report (Gjorgjioska et al., 2025). The voluntariness in the process of publishing information is in contrast with the EU regulation where ESG disclosure is required for some types of companies (see more CSRD art. 5). The Draft version of the new Law on accounting proposed mandatory disclosure of nonfinancial reports for companies with more than 500 employees.

2 Research Methodology

The main aim of the research is measuring the ESG maturity of Serbian and North Macedonian joint-stock companies, listed in the national stock indexes (BELEX15–9 listed companies and MBI 10–10 listed companies), which comprise the most liquid and market-leading companies in Serbia and North Macedonia, making them relevant carriers of ESG practices. One of the limitations of this research is that the analysis is focused only on the largest listed companies which may differ from other companies. Therefore, the results should be interpreted as indicative of leading companies, and not for all businesses. Furthermore, it should be noted that each of the two analyzed national stock indexes includes only one company from the construction sector. The selection of ESG indicators analyzed in this study was primarily based on the indicators included in the ESG Reporting Guide adopted by the Macedonian Stock Exchange (MSE). To ensure comparability, the research used general indicators applicable in a broader international context, aligned with internationally recognized ESG frameworks, including the Global Reporting Initiative (GRI), the Sustainability Accounting Standards Board (SASB), and relevant recommendations of the European Union. Given that ESG frameworks encompass a large number of indicators across the environmental, social, and governance dimensions, and considering the space limitations for presenting the results, this study focuses on a selected set of indicators that are common to the GRI

Standards, the ESRS, and the Macedonian Guide to ESG Reporting. Consequently, the exclusion of other potentially relevant ESG indicators may be considered a limitation of the research. Differences in the regulatory framework, particularly the existence of an ESG guide in North Macedonia and its absence in Serbia, may also have influenced the results.

The data used in this research were obtained from secondary sources - annual reports, financial reports, corporate governance questionnaires, publicly available on the web sites of analyzed companies, BSE and MSE.

For assessment of the ESG maturity of analyzed companies were measured 15 indicators, namely 5 for each of the ESG aspects. Namely, 1–5 indicators related to E (environment), 6–10 indicators related to S (social issues) and indicators 11–15 related to G (governance). The labels and their meaning are:

1. Formalized environmental management system (EMS)
2. Formalized waste management program or policies (selection, recycling etc.)
3. Greenhouse gas emissions (CO2 or other GHG emissions, values or intensity)
4. Energy consumption by type of source (renewable or non-renewable)
5. Water resources management (water consumption, reduction of use etc.)
6. Workforce structure (gender, education, age etc.)
7. Provided trainings (internal or external, number of trainings per employee)
8. Benefit programs for employees
9. Occupational safety and health management system
10. Number of workplace injuries
11. Structure of management and supervisory board/board of directors
12. Gender representation in managing bodies
13. Code of ethics, anti-corruption and conflict of interests' policies
14. Risk management system, including protection of personal data
15. Annual, ESG or sustainability reports (published on the web page of the companies).

The fulfillment of the prerequisites of each indicator was assessed on a scale of 0 to 2 points (where 0 means no publicly published information regarding the indicator, 1 means that there is some general, qualitative information about the indicator and 2 means that there is published quantitative and detailed information about the indicator). The maximum number of points for each group of indicators may be 10 points, while the total ESG index is 30. The final score of fulfillments of the ESG index is calculated as a ratio between the total number of points awarded and the total number of possible points, expressed in percentage.

$$\text{ESG Index} = \text{Points awarded}/\text{Maximum possible points} \times 100$$

Depending on the value of ESG index, analyzed companies may be classified in 5 groups of ESG maturity:

- 0–20% in "very poor" ESG maturity group,
- 21–40% in "poor" ESG maturity,
- 41–60% in "moderate" ESG maturity,
- 61–80% in the "good" ESG maturity and
- 81–100% in "very good" ESG maturity group.

In addition to the horizontal analysis of ESG maturity reached by companies, the authors applied a vertical analysis by each ESG indicator and also by each of the ESG aspects in BELEX15 and MBI10 indexes. Vertical analysis enables determination of the implementation of each ESG indicator individually and into the frame of E, S or G aspects. Vertical analysis presents an important analytical approach that gives very important signals about the weaknesses and strengths of ESG reporting on a national level that are not directly visible through individual analysis of the company's results.

3 Results and Discussion

In order to present the level of ESG maturity of the largest listed companies in both countries, the following graphs present the average ESG levels, level of E, S and G aspects of ESG, and more specified by analyzing each of the analyzed 15 indicators. An average ESG level of MBI10 companies is significantly higher (72%) compared with ESG maturity level index of BELEX15 companies in Serbia (44%). On average MBI10 companies show good ESG maturity, and Serbian BELEX15 companies are situated in the group with an average ESG maturity (Fig. 2).

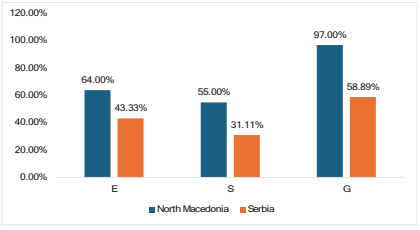


Fig. 1. An average level of maturity of ESG aspects in North Macedonia (MBI10) and Serbia (BELEX15)

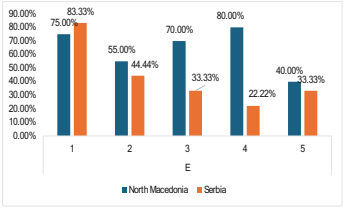


Fig. 2. An average level of maturity of E indicators in North Macedonia (MBI10) and Serbia (BELEX15)

Figure 1 presents the comparison maturity of each of the groups of indicators structured in E, S or G segments in both countries. In all segments MBI10 companies have shown better achievements. The most obvious difference in favor of MBI10 companies is evident in the G segment (with differences of 38,11%) where an average maturity indicator level of MBI10 companies is equal to 97%, compared to BELEX15 companies' value of 58,89%. It is interesting that MB110 and BELEX15 companies show the same trends of maturity level, with highest level of maturity in G segment, and lowest maturity level at S segment. The highest level of maturity by MBI10 companies is shown in G segment with 97% and by BELEX15 companies with 58,89%. The lowest maturity segment S is presented with 55% and 31,11% by MBI10 and BELEX15 companies, respectively.

The lowest level of maturity in the E segment by MBI10 companies is shown in indicator 5 (water resources management), while by BELEX15 by indicator 4 (Energy consumption by type of source). The best results are gained in indicator 4 by MBI10

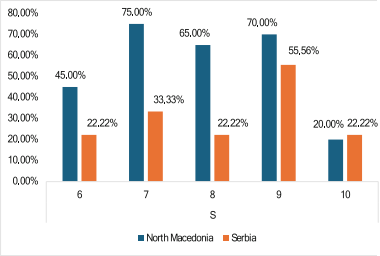


Fig. 3. An average level of maturity of S indicators in North Macedonia (MBI10) and Serbia (BELEX15)

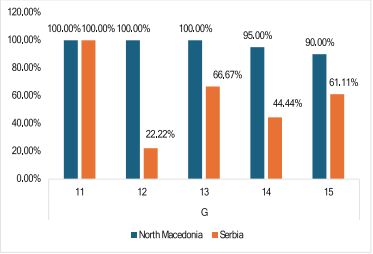


Fig. 4. An average level of maturity of G indicators in North Macedonia (MBI10) and Serbia(BELEX15)

companies, that is indicator 1 (Formalized environmental management system) in BELEX15.

Figure 3 shows that within the S dimension, MBI10 records its lowest value for Indicator 10, while BELEX15 shows the lowest values for Indicators 6, 8, and 10 (see Sect. 2.1). The highest value in MBI10 is observed for Indicator 7, whereas in BELEX15 the highest value is recorded for Indicator 8. In Fig. 4, the G dimension BELEX15 exhibits its lowest score for Indicator 12 and its highest for Indicator 11. Conversely, MBI10 shows uniformly high scores across all indicators, suggesting a more balanced application of corporate governance practices and the highest level of compliance with the assessed indicators (Table 1).

Table 1. Comparison of the average maturity level of indicators in E, S and G dimensions of ESG aspects of MBI10 and BELEX15

	E		S		G		ESG	
	E index	E Maturity level	S index	S Maturity level	G index	G Maturity level	ESG index	ESG Maturity level
North Macedonia	64%	Good	55%	Moderate	97%	Very good	72%	Good
Serbia	43,33%	Moderate	31,11%	poor	58,89%	Moderate	44,44%	Moderate

The comparison between MBI10 and BELEX15 companies shows significant differences in ESG maturity of analyzed companies. The average ESG maturity index in RNM shows 72%, which is 27,56% higher than the average ESG maturity index in RS (44,44%). Classified in groups, MBI companies have shown "good" ESG maturity, while BELEX15 companies have shown "moderate" ESG maturity. The most obvious differences are shown in the G dimension when MBI10 companies show average maturity of 97%, while BELEX15 companies show 58,89%. E and S dimensions also record a higher level of formalized procedures and transparency of Macedonian companies. The trend of stronger performance in the G dimension among MBI10 companies has been

in line with the comparative analysis. Historically, the G dimension has received greater attention from investors than the S and E dimensions, which have gained increased focus only in recent years (Matos, 2020).

In terms of the E dimension, MBI10 companies show stable and relatively high values (55–80%) with the best results accomplished for indicator 4 (80%). BELEX15 companies have gained a respective level of ESG maturity for the index E1 (83,33%), while all other indicators are considerably lower (22,22%–44,44%).

S dimensions of MBI10 companies record relatively high scores, with greatest achievements of indicator 7 (75%) and record low levels of S maturity of indicator 10 (20%) and average S maturity index of 55%. BELEX15 companies show lower scores starting from 22,22% for some indicators till 55,56% for indicator 9.

MBI10 companies show exceptionally high values for all indicators for the G indicators (90%–100%), indicating a high level of formalization, transparency and developed corporate governance mechanisms. G indicators at BELEX 15 vary significantly (22.22%–66.67%), with the lowest value for indicator 12 (22.22%), and highest value for indicator 11 of 100%. This indicates an uneven alignment of the principles of good corporate governance. The G indicators of ESG reporting in MBI10 companies represent the strongest side of ESG reporting in the RNM with significant contribution to increasing the overall ESG index. This may be a consequence of adoption of the CGC of MSE and due to the obligations for greater transparency of some joint stock companies stipulated by Law on trade companies. In this manner research in North Macedonia shows that thanks to the CGC and the stipulated obligation in Code of commercial companies, the level of the transparency of companies that are obliged to comply with CGC is on average 71%, which may be categorized in "good level" transparency (Gjorgjioska, et al., 2025).

4 Conclusion

Although a relatively high level of ESG maturity has been observed in North Macedonia, especially in the governance dimension, further strengthening of environmental and social aspects is required through the development of more specific policies, measurable objectives and regular reporting. The results for the Republic of Serbia indicate a lower level of implementation in all dimensions, especially in the social dimension. In this regard, the introduction of a more structured approach to ESG reporting, aligned with international standards such as GRI or EU regulations, as well as strengthening the transparency and availability of non-financial information is recommended. The results indicate that the development of a formalized ESG reporting framework can be a significant step for Serbia in improving corporate transparency and alignment with international standards.

In addition, for both countries, increasing institutional support, education of management and integration of ESG principles into corporate strategies are recommended, in order to achieve a higher level of sustainability and long-term competitiveness. Publishing well-organized structured nonfinancial reports, with illustration, tables, graphs and charts, that visually presents the data, dynamics, and targets, goals and objectives for further development of the companies will affect positive on the ESG maturity of companies in any sector of the both countries. If countries are more committed to achieving a

higher level of ESG maturity in the real economy sector, they may introduce a legal obligation to apply ESG reporting standards. It is expected that such measures will directly influence all companies, including those in the construction sector, encouraging them to improve their ESG performance. Once Serbia and North Macedonia adopt the provisions of the CSRD and incorporate them into their national legislation, future research can examine their impact on the level of companies ESG maturity, including the building sector.

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Barriers and Enablers for Transition to a Circular and Sharing Economy: Building and Construction Materials Circularity in Latvia

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Abstract. The shift to a circular and sharing economy (CSE) is increasingly recognized as an essential path towards sustainable construction. The current study aims to examine the main barriers and enablers affecting Latvia's shift to a CSE for building and construction materials. The primary structural, economic, social, technological, and regulatory factors that either support or impede the expansion of CSE projects in Latvia are to be identified and systematized in this study. The research synthesizes empirical findings from Latvian CSE initiatives on the sharing of construction materials, analyses national policy reports, and conducts an in-depth literature review. A systematic view is used to further organize the identified components, enabling a holistic assessment of the transition to construction sustainability. The study emphasizes that a coordinated policy strategy that incorporates regulatory clarity, economic incentives, digital solutions, and stakeholder participation is necessary for the shift to circularity for building and construction materials. Increasing these facilitators can greatly speed up behavioural change, improve resource efficiency, and promote long-term sustainable development.

Keywords: Barriers · Enablers · Circular economy · Sharing economy · Building and construction materials · Latvia

1 Introduction

With a significant portion of material consumption, waste production, and greenhouse gas emissions, the construction sector is widely acknowledged as one of the most resource-intensive in the world. Building and construction account for about one-third of all waste streams and about 40% of material consumption in the EU [1–3], making the industry a crucial lever for reaching goals related to resource efficiency and climate neutrality. Consequently, sharing economy (SE) and circular economy (CE) strategies have become more well-known as complementary frameworks for changing traditional linear patterns of production and consumption. While SE stresses better asset use through access-based and collaborative consumption models, CE concentrates on closing material loops

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through reuse, recycling, and regenerative design. These paradigms come together in the built environment around tactics like shared infrastructures, modular construction, adaptive reuse, and material circularity [4, 5]. Implementation is still disparate despite increased policy attention and technical advancements, especially in smaller economies like Latvia, where uptake is still constrained by institutional, structural, and cultural factors [6, 7]. The aim of this paper is to analyse the key barriers and enabling factors influencing Latvia's transition toward a circular and sharing economy (CSE) in the field of building and construction materials. Specifically, the paper seeks to (i) identify and systematize structural, economic, social, technological, and regulatory determinants affecting CSE initiatives; (ii) assess how these factors interact within Latvia's specific socio-economic context; and (iii) contribute to a policy-relevant analytical framework that supports the scaling and institutional embedding of circular construction practices.

2 Circular and Sharing Economy in the Built Environment

The circular economy (CE) has emerged as a new economic paradigm that seeks to decouple economic growth from resource consumption, including in the construction sector. CE is based on maintaining materials and resources in productive use for as long as possible through reuse, repair, refurbishment, and recycling, thereby minimizing waste generation and preserving material value throughout their lifecycle [3, 8]. The transition of the built environment towards a CE requires coordinated strategies involving multiple stakeholders, supportive governance frameworks, and systemic changes in production and consumption practices [9, 10]. Recent research highlights the growth of circularity and its significance for sustainability, which improves construction materials and energy efficiency and decreases emissions [2, 11].

The decrease of primary resource consumption will surely be positively impacted by the implementation of circularity principles, the use of eco-friendly materials, and reasonable building and demolition waste management, with a focus on digital solutions [9, 12, 13]. When applied to buildings, CE involves a shift from product-based to system-based thinking, covering every stage of the building lifespan.

The integration of life-cycle assessment tools into planning and procurement procedures, modular construction, material standardization, and design for durability and disassembly are important tactics [14]. Waste from construction and demolition accounts for a significant portion of the total waste stream, is inert and has a high volume and weight. The building materials circularity calls for organizational innovations like material passports, digital traceability systems, and secondary materials marketplaces, in addition to technological solutions like reusable parts and recycled aggregates. Higher utilization rates of underutilized assets are made possible by the sharing economy.

Shared equipment platforms, material exchange hubs, professional co-working spaces, and cooperative housing projects are examples of SE models in the construction industry. By coordinating stakeholders, boosting transparency, and lowering transaction costs related to sharing practices, digital platforms play a crucial enabling role [15]. When CE and SE are combined, hybrid systems are produced where common infrastructures and services strengthen material loops. Community-based reuse centers, digital marketplaces for reused parts, and shared modular buildings are a few examples. These

integrated strategies have the potential to improve accessibility and affordability while drastically lowering the demand for materials [16]. Implementing the CE at the material level encompasses standards that define circularity in building materials. The study examines measures intended to evaluate circularity at the material level, which are useful instruments for guiding implementation and decision-making procedures. Strategic, generic performance, and water usage indicators are among the different categories of indicators that are displayed. Waste hierarchy-aligned strategies are described, with a focus on reducing waste from building and demolition, reducing greenhouse gas emissions, preserving energy, and optimizing prices and water resources [17, 18]. As the experience that has been assessed within current research shows, effective results in the beneficial use of household construction and demolition waste can be achieved by creating and developing public platforms and exchange points, so that residents can transfer for further use construction waste that can be usefully used, taking into account difficulties in technology applications (IoT), cost and financial issues [19–22]. The current study corresponds with research carried out in the Baltic States, which discovered that Latvia's construction and demolition waste (CDW) management is different from that of Western and Northern European nations in a number of ways, including the fact that wood is a national renewable resource that is essential to boosting sustainability [7, 8, 23].

3 Building and Construction Materials Circularity in Latvia

As one of the biggest businesses in terms of material consumption, the construction sector is crucial to the expansion of Latvia's economy [22]. The construction sector could accelerate Latvia's attainment of sustainable development goals by raising demand for sustainable and circular building materials and construction products made from recycled or locally renewable natural resources [22, 23]. Due to its longstanding ties to forestry, wooden construction, and the untapped potential of contemporary wood use, Latvia has the potential to become a leader in the circularity of eco-friendly building materials. The available information shows that the existing system is more suitable for preparing for the reuse and recycling of large amounts of inorganic masses. On the other hand, in such product groups, where it is necessary to prove the quality and compliance of several different units with the existing product standards, as well as to provide appropriate documentation, such as doors, windows, roof covering materials, hygiene and sanitary equipment, radiators, floor covering, etc., this system does not return products to the market, as they require high costs in material testing and reuse [11, 23]. Table 1 shows the situation in Latvia, where the collected construction waste is divided into three groups: (1) waste from the demolition or removal of buildings, (2) waste from road and street repairs and (3) hazardous construction waste.

The authors argue that Latvian regulatory institutions could benefit from adopting this approach. A key prerequisite for the effective management of construction and demolition waste is the provision of clear, accurate, and comprehensive information on what constitutes such waste, how it should be managed, and how households can reduce disposal costs by separating reusable or recyclable materials from the general waste stream.

Table 1 Circular Construction waste after demolition or moving out

Construction waste after the demolition or removal of buildings:		Construction waste after road and street repairs:	Hazardous construction waste
Concrete, reinforced concrete, bricks, tiles, ceramic products, roof tiles, pavers, ceramic mixtures (pots, sinks, etc., plumbing) and also various plastic alloys, plywood, particle board, OSB, and metal.	Wooden structures, wooden construction structures with/ without metal admixture, gypsum products, insulation materials and foam, linoleum, gypsum sheets, aerated concrete, fib blocks, granite.	Asphalt, asphalt concrete, cement, bitumen, stones, rubble, sand, gravel, dirt.	Slate, asbestos, etc.

4 Barriers and Enablers for Transition to a CSE

From the standpoint of socio-technical transformation, Latvia can be described as functioning primarily under a linear construction regime, with niche circular processes remaining marginal and poorly institutionalized. To empirically examine household-level barriers and enablers for construction and demolition waste circularity in Latvia, a countrywide survey was undertaken and analysed in the years 2022–2023 [24]. 2,005 valid responses were obtained from the survey, which was intended for inhabitants between the ages of 18 and 75. This sample was representative in terms of gender, age distribution, area, education level, and type of residence. Continuing and supplementing the research, the authors conducted expert interviews in the summer of 2025 [24]. The questionnaire had 65 topics addressing respondents' experience with remodelling and construction activities, understanding of construction and demolition waste management alternatives, disposal practices, attitudes toward environmental implications, willingness to pay for legal waste collection, and opinions on institutional support. A five-point Likert scale, ranging from "definitely Yes" to "definitely No", was used to gauge responses to statements about attitudes. About 67% of those surveyed said they had completed building or remodelling projects in the last five years. Most of these activities took place in flats (47%) and private houses (36%), reflecting Latvia's mixed urban–suburban housing arrangement. In order to analyse behavioural variations between population groups, the survey additionally collected sociodemographic information (gender, age, education, income, and place of residence). Cost-related concerns appeared as one of the major hurdles to appropriate CDW management. While more than 60% of respondents said they would be ready to lawfully dispose of construction waste even if it meant paying extra, a sizable portion also admitted that they might select less expensive options despite possible environmental harm. Income level was found to be statistically significant: respondents with higher incomes (>€2000 per household member) showed a greater willingness to pay for environmentally sound waste management, while households

with lower incomes were significantly more likely to prioritize cost over environmental considerations. This demonstrates that, especially in the household sector, financial feasibility continues to be a crucial factor in determining circular behaviour.

Despite somewhat positive environmental sentiments, actual disposal practices demonstrated considerable reliance on informal or environmentally destructive disposal methods. Burning waste materials (29%) and putting CDW in mixed household waste bins (34%) were the most popular methods. Participation in formal circular systems is reduced by factors such as perceived complexity of legal disposal procedures, lack of specialized collection routes, and limited proximity to sorting facilities. Many respondents were unsure of the regulations pertaining to renovation activities, and there was inconsistent awareness of the difference between hazardous and recyclable construction debris. This creates a structural barrier that supports informal practices and inhibits engagement with circular solutions. More than 90% of participants underlined the need for state-supported programs to lower the cost of hazardous and construction waste disposal. Respondents also highlighted better municipal communication, clearer guidance from waste managers, and tougher enforcement by local authorities as useful ways for enhancing construction and demolition waste management. 45% of respondents indicated readiness to pay additional rates for waste collection services. A large number of respondents indicated interest in systems that would facilitate the exchange or reuse of extra building materials. Such initiatives work as practical enablers by cutting transaction costs and facilitating household participation [10, 25]. A summary of barriers and enablers can be seen in Table 2.

The results demonstrate that economic sensitivity, unclear regulations, inadequate infrastructure, and behavioural inertia continue to impede Latvia's shift toward circular and sharing economy practices in building materials. Despite the fact that most households have positive attitudes toward the environment, disposal habits are still primarily motivated by convenience and cost, indicating a persisting gap between intention and conduct [22, 23]. While higher-income respondents show a greater readiness to pay for environmentally sound solutions, lower-income groups are particularly price-sensitive, highlighting the significance of tailored financial incentives. There is a lot of latent potential for hybrid circular-sharing systems. Participation barriers could be substantially reduced by digital platforms, centralized reuse centres, and enhanced municipal communication [22]. In general, Latvia is still deeply ingrained in a construction regime that is primarily linear. In order to connect household behaviour with institutional support, accelerating the circularity of building materials would require concerted governmental action that combines economic incentives, digital innovation, and clear regulations.

Table 2 Barriers and enablers for Transition to a Circular and Sharing Economy for Building and Construction Materials

Factors	Barriers	Enablers
Economic	Significant sensitivity to disposal prices; fewer financial incentives; lower-income families are more likely to choose less expensive, ecologically harmful options.	Higher-income respondents show increased willingness to pay for proper disposal.
Regulatory	Reuse of construction materials is restricted due to their early classification as waste; state, municipal, and waste disposal operator responsibilities are divided; and enforcement is insufficient.	The public supports state-funded initiatives, and they also favour increased municipal participation and more transparent processes.
Infrastructure and accessibility	Lack of simple collection routes, perceived complexity of legal disposal procedures, and limited proximity to sorting and recycling facilities	Potential for hybrid circular-sharing service models; interest in material exchange platforms; and the emergence of centralized sorting and reuse hubs
Information and awareness	Only roughly half of households feel adequately educated; there is a lack of clarity regarding the distinction between hazardous and recyclable CDW, and the services that are provided are not easily visible.	High awareness of the positive environmental effects of reuse and receptivity to recycled building materials.
Governance and collaboration	Initiatives for sharing and reuse are not well integrated into official waste management systems, and experimental programs lack consistent support.	Wide public expectation of coordinated action; willingness to adopt circular practices if institutional backing increases.
Social and behavioural	Convenience-driven unofficial behaviours (burning, disposing of mixed garbage), the intention-behaviour gap, and enduring linear consumption patterns.	Stronger pro-circular sentiments are shown by respondents who are women, younger adults, and higher educated; sorting of items is more common in rural households.

5 Conclusions

Since construction waste is a significant waste stream that can be converted into a resource, one of the most crucial paths is the application of waste circulation principles for building construction and deconstruction. The proper management of construction waste produced in households and the inhabitants' understanding of the tasks to

be completed must be greatly improved in order to accomplish this as effectively as feasible.

Households must be fully aware of the need to sort building and demolition waste at source and turn it over for recycling or reuse, and municipalities should build the necessary infrastructure for this kind of waste collection. The collection system needs to be easy to understand, straightforward, and unambiguous. The cost of waste collection and management should also be comprehensible to the general public. More than just technology replacement is needed for the construction industry to shift to circular and sharing economies; significant structural changes in material flows, economic models, and governance structures are also necessary. Latvia faces both a problem and an opportunity in overcoming outdated systems while capitalizing on the momentum of evolving European policies.

Comprehending barriers and enablers serves as a basis for creating efficient policy tools and business tactics. In the end, collaborative governance, digital innovation, and sustained commitment from all stakeholders are necessary to advance building materials circularity.

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Societal and Educational Dimensions: Awareness, Equity, Skills, and Capacity-Building for Sustainable Transitions

From Prefabrication to Reuse: Educational Strategies for Circular Construction Using Hands-On Disassembly

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Abstract. This study presents the outcomes of a two-part workshop conducted with students at the University of Applied Life Sciences Campus Vienna (Hochschule Campus Wien). The first workshop engaged participants in the hands-on disassembly of a prefabricated bathroom unit, primarily constructed in timber, with the goal of maximizing the reuse of its components. Students systematically assessed five product groups from ceiling and wall assemblies—load-bearing structure, paneling, fasteners, vinyl, and tile cladding—according to four parameters: disassembly complexity, level of disassemblability, reuse potential, and recycling potential. Components such as vinyl and tile cladding were found to be highly complex, non-disassemblable, and non-reusable, often due to moisture-tight connections, which, while essential for durability, limit circularity. In the second workshop, students applied their findings to a design–build exercise, developing an open-air bar using recovered timber and locally excavated clay. The process encouraged critical reflection on material selection, construction methods, and integration of circular principles into real-world design scenarios. The workshops employed a "learn by doing" didactic approach, emphasizing experiential learning, collaboration, and reflection. By engaging with materials and confronting challenges of disassembly, reuse, and moisture management, students developed a deeper understanding of circular construction practices. Overall, the workshops demonstrate the potential of hands-on, circularity-focused education to equip future architects and engineers with practical skills and critical awareness for implementing circular economy principles.

Keywords: Student workshop · Design-Build · Timber construction

1 Introduction

The construction industry is a major driver of environmental degradation, accounting for approximately 39% of global greenhouse gas emissions and about one-third of all waste generated worldwide [1, 2]. Achieving net-zero targets by 2050 therefore requires a fundamental transformation of the sector, including a shift away from carbon-intensive materials toward renewable alternatives such as timber, which sequesters CO_2 in its

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biomass [3, 4]. Due to its comparatively low embodied energy and capacity for long-term carbon storage, timber represents a promising substitute for conventional structural materials [5]. However, these environmental benefits are only realized if the biogenic carbon stored in timber remains "locked in" the built environment across multiple life cycles rather than being released prematurely through incineration or biodegradation [6, 7]. To support higher-value material circulation, increasing attention has been directed toward Design from Disassembly (DfromD), a downstream design strategy that matches existing inventories of salvaged building components with the requirements of new architectural projects [8]. Unlike Design for Disassembly—which focuses on enabling future material recovery during the planning of new buildings—DfromD provides an immediate pathway by leveraging the existing building stock as a material reservoir [9]. Reusing reclaimed structural elements can significantly reduce embodied emissions by avoiding extraction, processing, and manufacturing stages associated with new materials, as well as impacts from end-of-life treatment [10, 11]. Despite these advantages, widespread adoption remains limited. Reuse often requires non-standard design workflows, while reliable technical information on the condition and load history of reclaimed materials is frequently unavailable. In addition, many practitioners are still trained within conventional mineral-based construction paradigms, and heightened risk perceptions among stakeholders further hinder the uptake of reclaimed structural components [12–14]. As a result, traditional downcycling pathways remain common, limiting the circular potential of timber reuse.

However, the growing adoption of prefabricated timber systems with dry and reversible connections offers favorable technical conditions for scaling reuse in the future. Several studies therefore emphasize the importance of education in fostering the knowledge and professional cultures required to implement circular construction practices [15]. Higher education institutions are particularly well positioned to support this transition due to their capacity to influence both individual behavioral change and future professional practice [16]. Within this context, hands-on learning environments such as design–build provide a promising framework for integrating research and education through real-world experimentation. These environments enable students and researchers to translate theoretical concepts into practice while testing prototypes under controlled yet realistic conditions [17].

Against this background, this paper investigates how hands-on educational formats can contribute to advancing circular timber construction by linking experiential learning with material experimentation. Specifically, the study presents a two-part workshop conducted with students at Hochschule Campus Wien that combined the disassembly of a prefabricated timber-based bathroom unit with a subsequent design–build exercise using reclaimed materials. By documenting the disassembly process, evaluating the reuse potential of different construction components, and translating these findings into a small-scale architectural intervention, the paper explores practical challenges and opportunities associated with timber reuse and highlights the didactic value of experiential learning for circular design education.

2 Methods: Workshop Structure and Assessment Protocol

The study was implemented across two consecutive workshops combining systematic disassembly with a subsequent design–build application. In total 30 students participated (20 architecture students; 10 students from the Sustainable Resource Management programme). The activities were supervised by six experts with complementary expertise in architectural research, carpentry, architectural practice, sustainable assessment, structural timber engineering, and building physics. This interdisciplinary supervision supported both technical decision-making during disassembly and the translation of findings into design solutions.

In the first Workshop the students carried out the systematic disassembly of the prefabricated timber-based unit. To organize work efficiently and to simulate realistic deconstruction workflows, students were divided into dedicated functional teams:

- Inventory & storage team: catalogued recovered components, labelled elements and organized temporary storage.
- Documentation team**:** filmed disassembly sequences, photographed details and maintained a process log for later analysis and dissemination.
- Large-assembly removal team: removed wall and ceiling assemblies and managed safe handling of bulky components.
- Layer separation team: removed layered finishes, fillers and joint compounds to expose substrate conditions.
- Fixture removal team: unscrewed and recovered fixtures and fittings, sorting items that could be returned or re-used.

Teams followed a standardized assessment protocol. Five product groups were analysed: (1) structural timber elements, (2) interior paneling, (3) mechanical fasteners, (4) vinyl wall cladding, and (5) ceramic floor tiles. Each recovered component was evaluated individually by each student according to four parameters: disassembly complexity, level of disassemblability, reuse potential, and recycling potential. The assessment was conducted using a five-point scale, where 1 indicated very low circular potential (high disassembly complexity, non-disassemblable, non-reusable, and non-recyclable), and 5 indicated very high circular potential (low disassembly complexity, high disassemblability, high reuse potential, and high recyclability). Intermediate values represented gradual variations between these extremes. This scoring approach enabled students to comparatively evaluate the circular performance of different construction components while maintaining a consistent assessment framework across all teams.

In the second workshop, an interdisciplinary design-build exercise was organized with the goal of designing and constructing an open-air bar for the campus, using reclaimed timber elements and clay excavated on site. For this phase student roles were organized into four coordination teams:

- Financing team: budget planning and fundraising;
- Procurement team: sourcing supplementary materials (local suppliers, stores);
- Construction team: on-site assembly and logistical coordination;
- Design/planning team: development of detailed drawings and assembly details adapted to available reclaimed elements.

3 Results: Technical Observations and Material Outcomes

3.1 Technical Observations from Disassembly

The disassembly exercise produced consistent technical findings across teams. Structural timber elements and mechanically fastened paneling exhibited the highest circular potential: these components were frequently removable intact, required only modest post-processing (cleaning, trimming, surface finishing) and could be re-integrated in new assemblies with reversible mechanical connections. Screw-based and other dry mechanical fasteners significantly eased separation and preserved component integrity. By contrast, concealed connections and permanently bonded interfaces (glues, bonded laminates) were primary causes of damage during removal and thus major impediments to reuse. Ceramic floor tiles and vinyl wall cladding showed markedly lower circular potential. Tiles were typically bonded with thin-set mortars and installed in combination with liquid-applied or sheet waterproofing systems; removing tiles intact was time-consuming and generally destroyed both tile and waterproofing layers. Vinyl coverings were commonly adhered or embedded in screed; adhesive residues and substrate contamination prevented clean separation and reduced practical recyclability. A concrete procedural observation concerned hidden fasteners: several screws were found beneath glued panels, demonstrating that screw heads must remain accessible if future disassembly is to be feasible. This operational detail proved decisive for both the disassembly speed and the quality of recovered elements.

3.2 Logistical, Organizational and Material Handling Outcomes

The team-based organization of the workshops revealed several logistical challenges. Cataloguing and inventorying the recovered materials aided traceability, yet maintaining an overview of material availability proved difficult because elements were stored across multiple locations. The absence of a single, well-organized depot increased search times and complicated procurement planning. Practical constraints also arose from the condition of the materials: reclaimed timber occasionally contained embedded screws or metal fragments, what in real projects could lead local workshops to refuse processing to avoid damage to cutting machinery, emerging as a major barrier to upcycling salvaged wood. Similarly, locally excavated clay required sieving and cleaning before it could be safely used, increasing preparation labour. In addition, inconsistent labelling and incomplete documentation reduced the immediate usability of some components and hindered the effective match-making between available materials and design needs.

3.3 Design–Build Outcomes, Adaptations and Innovations

The design–build phase allowed students to translate technical constraints into creative designs. Participants reported that working within the limitations of available materials increased their awareness of circular construction processes and stimulated inventive solutions rather than restricting creativity. Initial design intentions were adapted to accommodate material availability and condition; for example, reclaimed glass blocks sourced through a second-hand market, which had not been part of the original plan, were

opportunistically integrated and enhanced the final composition. To preserve future reuse potential, students developed reversible connection systems: where bonding would have reduced disassemblability, timber framing and batten structures were used to mechanically retain modules, resulting in three modular units that are fully disassemblable and reusable. Recovered timber was employed both structurally and non-structurally, forming the primary structure of the bar and of a small storage area as well as interior and rear wall cladding, while some panels were stored for future use or partially repurposed in the bar substructure. In cases where reclaimed equivalents were unavailable, certain exterior lamellas were procured new, demonstrating practical decision-making within circular design constraints.

4 Discussion: Educational Value and Broader Implications

The workshops adopted a "learn by doing" pedagogy grounded in experiential learning and design–build practice, generating several educational benefits.

- **Tacit knowledge acquisition:** Students gained hands-on understanding of connections, adhesives, and layered construction systems that are difficult to convey through drawings or lectures. The disassembly process revealed practical aspects such as tool use, dismantling forces, and hidden sealing layers that determine whether components can be reused. In several cases, screws concealed beneath glued panels complicated material recovery, illustrating how minor design decisions—such as accessible fastener heads—strongly influence the future disassemblability of components and strengthen students' confidence in construction-related decision-making.
- **Critical material literacy:** Direct interaction with reclaimed elements encouraged students to develop a more nuanced understanding of material quality, variability, and the interventions required for reuse. Rather than treating materials as abstract design inputs, students evaluated trade-offs between embodied carbon savings, refurbishment effort, and structural or safety considerations. These observations illustrate the additional labour and processing steps often associated with reuse-based construction.
- **Collaborative problem-solving:** Disassembly tasks required coordination, sequencing, and reflection on safety and documentation procedures. Student teams organised themselves into functional groups responsible for inventorying recovered components, documenting the process, removing assemblies, and separating layered materials. These activities resemble professional deconstruction workflows and foster collaborative problem-solving skills relevant to circular construction practice.
- **Immediate translation to design:** The subsequent design–build exercise required students to translate constraints encountered during disassembly into design decisions. Limited quantities of intact materials and dimensional inconsistencies encouraged reversible connections and adaptable design strategies. Rather than restricting creativity, reclaimed materials often stimulated innovative solutions.

Beyond these learning outcomes, the workshops also revealed logistical challenges typical of reuse-oriented construction. Maintaining an overview of available materials proved difficult due to fragmented storage locations and limited space. Although an inventory system was implemented, dispersed storage increased the time required to

locate suitable components and complicated procurement during the design–build phase. These experiences highlight the importance of dedicated material depots, systematic documentation, and pre-sorting of recovered elements to support efficient reuse workflows. Despite these challenges, the workshops generated strong engagement among participants. Students reported that working directly with reclaimed materials increased their awareness of the technical, regulatory, and logistical complexities of circular construction. The process was widely perceived as motivating and exploratory rather than restrictive, and adapting design concepts to available materials often produced more diverse architectural outcomes.

Taken together, these results confirm and illustrate the potential of practice-based educational formats as experimental environments for circular construction research [15, 16]. Design-build Living Lab settings within universities can function as intermediary spaces between research, teaching, and practice, enabling small-scale material experiments while generating empirical insights [17]. Disassembly-based learning modules can therefore be integrated into architecture and engineering curricula as workshops, design studios, or interdisciplinary courses, potentially in collaboration with demolition companies, construction firms, or municipal material depots. Overall, experiential learning formats appear particularly effective for teaching circular construction principles due to the integration of technical, environmental, and design judgements within a single process, bridging the gap between circular economy theory and construction practice.

5 Knowledge Gaps and Future Directions

From a didactic perspective, working on disassembly and reuse allowed students to experience firsthand the advantages of reversible connections and how early-stage design decisions facilitate future material recovery. Observing the impact of accessible versus concealed fasteners reinforced the importance of design choices for disassemblability, while engaging with layered assemblies and adhesives highlighted practical constraints that affect reuse potential. These experiences also exposed students to the challenges inherent in timber reuse, such as hidden screws, embedded metal fragments, and variable material conditions. Addressing these issues required careful handling, problem-solving, and adaptation—skills that cannot be fully conveyed through lectures alone. Students gained material literacy, practical decision-making experience, and collaborative coordination skills, seeing how technical, environmental, and design considerations intersect in real-world circular construction. These conclusions are based on qualitative statements and observations gathered during the workshops, informal discussions, and reflections from the teaching team and participants.

For future educational development, these findings suggest that hands-on engagement with recovered timber should be expanded and systematically integrated into architectural and engineering curricula. Empirical exercises in disassembly, coupled with design–build applications, provide a unique platform for teaching circular construction principles, enabling students to develop both the practical skills and critical judgment necessary to implement timber reuse strategies in professional practice. Extending this approach to different materials, project types, and collaborative contexts could further enhance its pedagogical impact.

Future research could further strengthen the analysis of circularity by integrating quantitative assessment metrics, such as disassembly time per layer, the percentage of components recovered intact, or mass recovery rates by material group. Such indicators would support a more systematic evaluation of the efficiency and effectiveness of reuse-oriented construction systems and provide additional insights into the relationship between design decisions and material recovery performance.

6 Conclusions

The workshops conducted at Campus Vienna demonstrate that hands-on disassembly and reuse exercises provide benefits that extend beyond technical familiarity. They foster material awareness, reveal systemic barriers to circular construction, particularly those related to moisture-proofing and adhesive systems, and create a safe environment in which students can experiment with circular design strategies. Such educational initiatives complement technological and regulatory innovation by preparing future architects and engineers to engage with reclaimed materials and circular design processes. At the same time, they offer opportunities to generate small-scale empirical insights into disassembly and reuse practices. To unlock the full reuse potential of timber and accelerate the transition toward circular construction, targeted empirical research, standardized testing protocols, and improved documentation systems, such as material passports aligned with emerging standards, will be essential.

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Building Transitional Skills for a Sustainable Construction Ecosystem: Educational Innovation and Societal Impact of the BuildSkills Academy Project

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Abstract. The twin green and digital transition is reshaping the built environment and generating urgent demand for new competences across the construction ecosystem. In this context, Vocational Education and Training (VET) must move beyond static provision models and adopt more adaptive and quality-oriented approaches. This paper analyses the BuildSkills Academy (BSA) as a transnational framework for supporting sustainable transitions through skills intelligence, curriculum enrichment, provider self-assessment and certification. It examines how BSA addresses awareness, equity, skills development and institutional capacity-building in construction. Methodologically, the paper combines literature on sustainable construction, circularity, digitalisation and VET transformation with a qualitative analysis of project materials on skills-gap analysis, BESM, pilot implementation, quality assurance and certification. Findings show that BSA contributes by translating transition priorities into structured topical areas, occupations and competences; supporting VET providers through a three-step process of self-assessment, gap identification and enrichment; testing transferability through twelve pilot courses across EQF levels and national contexts; and linking curriculum innovation with external validation and certification principles.

Keywords: Vocational Education and Training · Sustainable transitions · Built environment · Green and digital skills · Capacity-building

1 Introduction

The built environment sits at the centre of current sustainability debates because it concentrates major environmental, social and economic pressures. Construction remains highly dependent on resource extraction, energy use and fragmented decision-making, yet it is increasingly expected to deliver decarbonisation, climate adaptation, circularity, healthier living conditions and digitally enhanced performance. These expectations imply not only technological change but also a reconfiguration of professional roles, occupational standards and learning pathways.

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Recent literature shows that sustainable transformation in construction cannot be achieved through regulation and innovation alone; it also depends on whether education and training systems can anticipate and support change. Digital tools such as BIM, material databases, data-driven monitoring and digital twins are recognised as enablers of circularity and lifecycle optimisation, but their uptake remains uneven and is often constrained by skills deficits and weak coordination between training supply and labour-market demand. At the same time, VET research stresses that sustainability-oriented transitions require educational models able to connect green transformation, social justice, lifelong learning and institutional responsiveness.

In the construction sector, skills needs are evolving rapidly in areas such as energy-efficient design, circular material flows, sustainable procurement, indoor environmental quality, health and well-being, risk management and AI-supported coordination. Yet educational provision often remains slow to adapt, and the recognition of emerging green and digital competences is still fragmented across national systems. The BuildSkills Academy (BSA) addresses this gap through a pan-European architecture that combines skills-gap analysis, curriculum enrichment, provider self-assessment, quality assurance, piloting and certification.

2 Educational Transitions in the Built Environment

Research on sustainable construction increasingly emphasises that environmental performance cannot be separated from knowledge infrastructures. Çetin, De Wolf and Bocken's [2] work on the "circular digital built environment" is especially relevant because it shows that digitalisation should not be treated as an autonomous innovation stream, but as an enabling condition for circular-economy practices through improved traceability, data integration and collaborative lifecycle decision-making. This perspective is particularly important for the present paper because it supports the interpretation of digital tools not merely as technical upgrades, but as part of a broader sustainability transition in the built environment.

A second strand of literature concerns educational responses to sustainable construction. Koukou et al. [3] argue that integrated and transnational approaches are necessary to equip students and professionals with the competences required for sustainable and healthy buildings, especially when training must combine technical content, multidisciplinarity and practice-oriented learning. More broadly, this line of research suggests that energy transition, circularity, adaptive reuse and health-oriented design cannot be effectively mainstreamed through isolated modules alone, but require deeper curricular restructuring and stronger alignment between educational provision and sectoral transformation priorities.

A third strand concerns green skills and curriculum responsiveness more broadly. Recent VET scholarship shows that educational institutions often face persistent gaps between declared sustainability ambitions and the actual competences produced through curricula. The issue is not simply whether new content is added, but whether providers are able to revise course design, assessment methods, staff development and labour-market linkages in ways that remain responsive over time. In this sense, sustainable transitions reveal structural weaknesses in how educational systems sense, translate and act on changing sectoral demands.

Finally, the VET literature [1] increasingly foregrounds equity and justice. Sustainable transitions create new opportunities, but also new divides related to age, gender, educational background and access to lifelong learning. A just-transition perspective therefore requires VET not only to support employability, but also to widen access to emerging competences and reduce barriers to participation in future-oriented occupations. Avis explicitly argues for a broader conceptualisation of VET that moves beyond instrumentalism and engages more directly with just transitions.

Taken together, these debates reveal a clear analytical gap. Many initiatives address only one dimension of the transition challenge, such as digital skills, green curricula, certification or stakeholder engagement. Fewer contributions propose an integrated framework combining skills intelligence, pedagogical redesign, provider self-assessment, quality assurance and competence recognition in the construction ecosystem. It is within this gap that the present paper situates the analysis of the BuildSkills Academy.

3 Aims and Methodology

This paper investigates the educational and societal contribution of the BuildSkills Academy (BSA) as a transition-oriented VET framework for the built environment. It examines how green and digital agendas are translated into topical areas, occupations, skills and learning outcomes; how the project supports provider capacity through self-assessment, skills-gap identification and course enrichment; and how awareness, stakeholder participation, circularity and inclusion are embedded in the project logic. This perspective aligns with scholarship arguing that sustainability-oriented VET depends not only on updated technical content, but also on institutional responsiveness and collaborative learning.

Methodologically, the paper adopts a qualitative document-analysis approach within a practice-based perspective. The empirical corpus includes key BSA outputs on skills mapping, BESM, pilot syllabi, validation, adaptation, external quality assessment and certification, making it possible to trace the initiative from skills diagnosis to methodological design, piloting, validation, quality assurance and recognition.

The analysis was carried out in four steps. First, the documentary corpus was reviewed to identify recurring analytical categories across the project, including topical areas, occupations, transitional skills, quality criteria, validation mechanisms and certification pathways. Second, the internal logic of BESM was reconstructed by examining how self-assessment, custom skills-gap identification and enrichment interact within the digital platform. Third, pilot implementation evidence was compared across the course syllabi and the thematic-group validation report to assess transferability across EQF levels, national settings and thematic domains. Fourth, findings from project outputs were interpreted against the literature in order to distinguish project activities from the paper's analytical claims. This analytical design is coherent with recent work on sustainable VET, which emphasises the importance of reading educational change not only through curricular content, but also through collaborative and organisational learning processes [5].

To improve interpretive robustness, the paper triangulates methodological, validation and external-quality documents rather than treating any single deliverable as

self-sufficient evidence. This is especially important in project-based research, where implementation outputs may otherwise be mistaken for validated outcomes. The interpretive stance adopted here is therefore aligned with recent debates on VET for sustainable futures, which call for more reflective and transformative approaches to skills development rather than purely instrumental readings of training provision [4].

4 The BuildSkills Academy Framework

The evidence shows that BSA is structured as a multi-layered framework rather than as a single training package. Its first layer is the identification of sectoral needs through five main topical areas: Net-Zero Carbon Emissions, Climate Resilience and Adaptation, Circular Economy Practices, Sustainable Materials and Sourcing, and Occupant Health and Well-being. These are complemented by transversal transition domains such as Life Cycle Assessment, BIM, Digital Tools and Data Analysis, and Collaboration and Project Management. This is relevant because digitalisation is treated as a cross-cutting enabler of all transition domains instead as an isolated pillar.

The skills framework was developed through ESCO analysis, review of European and national sources, and validation activities involving surveys, roundtables and stakeholder feedback. The resulting architecture covers 38 occupations across the construction sector and the building lifecycle. Validation activities highlighted the high priority of net-zero construction, circularity, sustainable materials and climate resilience, while also revealing mismatches between industry priorities and current educational provision. This diagnostic layer is followed by BESM, which translates the skills framework into an operational device for course redesign. BESM is structured around three linked steps: self-assessment, skills-gap identification and enrichment. Through the digital platform, VET providers map their existing or planned courses, identify missing green and digital competences, and receive recommendations on how these gaps can be addressed. The methodology considers not only syllabus content, but also teaching methods, assessment practices, trainer preparedness, learner guidance and quality assurance.

A further layer is represented by piloting, validation and certification. The twelve pilot courses translate the framework into concrete educational offers across countries, EQF levels and thematic groups; thematic-group validation provides external sectoral feedback on the syllabi; and the certification component establishes a structured process for assessing curricula and training materials against defined criteria linked to learning outcomes and EQF levels.

5 Results

5.1 Transition Priorities and Competences

The first major result concerns the operationalisation of transition priorities into a structured and teachable competence architecture. BSA does not treat the twin transition as a generic policy narrative; instead, it converts it into five topical areas, 38 occupations and a refined set of occupation-linked competences for the construction ecosystem. This is significant because recent literature has shown that sustainability agendas often remain too broad unless they are translated into concrete competence domains and linked to sector-specific pedagogical decisions.

The project identifies 178 skills for transformation in Net-Zero Carbon Emissions, 110 in Climate Resilience and Adaptation, 129 in Circular Economy Practices, 97 in Sustainable Materials and Sourcing, and 104 in Occupant Health and Well-being. Particularly relevant is the fact that Circular Economy Practices emerges as one of the strongest areas for new skills and competences. In other words, BSA does not merely mention circularity; it gives it an operational structure through subareas such as renovation and retrofitting expertise, circular economy principles and practices in construction, design for deconstruction, material-flow management, waste-reduction techniques, digital material databases, and sustainable procurement.

This result is consistent with studies arguing that digital tools and circularity in the built environment should be understood together rather than as separate innovation streams. In that respect, the BSA framework reflects the logic of the "circular digital built environment", where digitalisation supports lifecycle intelligence, traceability and more effective circular practices.

5.2 Provider Capacity-Building

The second result concerns provider capacity-building. BESM is not only a course-enrichment device, but also a provider-level capacity-building mechanism. Through the digital platform, VET providers are asked to examine the content, teaching methods, assessment strategies, industry alignment and quality characteristics of an existing or planned course, and then receive a report indicating where green and digital competences are missing and how these gaps might be addressed.

BESM operationalises a model of institutional learning. The self-assessment logic includes course background, teaching methods, student assessment, quality assurance, career guidance, stakeholder consultation, staff development and learner-centred provisions. This broader scope suggests that BSA is addressing the organisational preconditions for sustainable VET transformation, not only curriculum content. This interpretation is consistent with recent VET literature, which argues that sustainable transitions cannot be addressed through isolated modules alone, but require provider adaptability, collaborative arrangements and organisational reflection.

In this sense, BSA's main educational innovation lies not only in the identification of missing skills, but in the creation of a repeatable mechanism through which providers can diagnose, revise and progressively improve their own provision. This point is particularly relevant for construction-related training, where technological and regulatory change can quickly make conventional course structures obsolete.

5.3 Pilot Transferability

A third result lies in the pilot architecture and the evidence of transferability. The project transfers its results into twelve pilot courses in six countries, involving 300 trainees and aiming to engage 100 VET providers, 1,000 companies and at least 100 VET–industry collaborations. The pilot syllabus documentation confirms that the courses span EQF levels 3 to 7 and include both enriched existing provision and newly designed courses.

The pilot portfolio demonstrates thematic breadth without losing sectoral focus. This breadth suggests that the framework is transferable across different occupational

profiles and levels of complexity while remaining anchored to strategic priorities of the built environment.

The validation report strengthens this claim. Trainers received consolidated recommendations from the thematic groups, reviewed the relevance and feasibility of each suggestion, and decided whether it should be reflected in the syllabus and/or training materials. In the circular-economy area, validation outcomes were especially strong: the review process confirmed relevance, applicability and quality of the developed syllabi, and emphasised the value of involving external experts to ensure labour-market alignment and pedagogical robustness (Table 1).

Table 1. Comparative summary of BSA pilot courses and validation outcomes.

Cluster of courses	EQF	Topics	Transition focus	Evidence of outcome
1. Resilient Buildings and Cities; 2. Smart, Resilient & Circular Cities	5	Environment / Energy Efficiency	Resilience, circularity, sustainable urban transition	Fully validated on learning outcomes, labour-market relevance, applicability and adaptability.
3. Construction Technology; 4. BIM	4–5	Design and Engineering / New Building Materials	Technical innovation, digitalisation	Supports transferability across technical and digital domains.
5. Circular Waste Management; 6. Circular Economy and Waste Management	4–7	Circular Waste Management	Circular economy, waste reduction, LCA-oriented thinking	Strong relevance to missing sector skills and practical applicability
7. Energy Management for Buildings; 8. Energy Efficient Installation in Buildings	3–4	Energy Efficiency	Decarbonisation, energy performance	Aligned with upskilling needs in energy-related construction practices
9. Work Safety in Construction; 10. Risk and Reliability in Health and Safety	3–6	Environment / Health and Safety	Safety, implementation quality, risk management	Broad applicability across occupational levels and contexts

(*continued*)

Table 1. (*continued*)

Cluster of courses	EQF	Topics	Transition focus	Evidence of outcome
11. Bio-inspired innovation and design for sustainable engineering; 12. Digitalization and Sustainable Development	6–7	Design and Engineering / New Building Materials	Advanced innovation, AI, sustainability	Demonstrates framework adaptability to emerging and higher-level topics

5.4 Quality Assurance and Certification

The fourth result concerns external alignment and recognition. BESM explicitly integrates quality-assurance thinking into the course-improvement logic, and the broader project architecture frames quality assurance as a constitutive dimension of course enrichment rather than an afterthought. The grant documentation makes clear that the methodology and adaptation procedure were designed to be underpinned by a quality-assurance cycle aligned with EQAVET.

At a second level, the project moves toward recognition infrastructure. The certification scheme is intended for the assessment and certification of curricula and training materials developed within the project, with the objective of ensuring that learning outcomes are aligned with the appropriate EQF level and that training materials meet the necessary quality standards. Project and grant documents also frame certification as part of a broader effort to bridge fragmented competence-recognition frameworks across Member States and to create a recognisable label for transitional skills and competences in the construction sector.

This result is analytically important because it moves BSA beyond the level of pedagogical experimentation toward that of institutional infrastructure. Innovative courses have greater value when the competences they generate are visible, comparable and potentially recognisable across contexts. This argument is also consistent with broader VET debates that call for stronger systemic connections between curriculum innovation, institutional quality and sustainable futures [4].

6 Discussion

The evidence suggests that the principal originality of BSA lies in the way it integrates skills intelligence, educational redesign, digital support, provider self-assessment, stakeholder validation, quality assurance and competence recognition into one coherent framework. In many existing initiatives these dimensions remain separated. BSA

is analytically relevant because it connects these layers in a way that supports both educational innovation and ecosystem coordination. In this sense, the project can be interpreted not only as a training initiative, but as an emerging governance model for transition-responsive VET in the built environment.

A particularly relevant implication concerns circularity. Circularity is not a marginal topic within BSA, but one of its strongest structured competence domains. It is embedded in the topical area "Circular Economy Practices", reinforced by "Sustainable Materials and Sourcing", and operationalised through subareas such as design for deconstruction, material-flow management, digital material databases and sustainable procurement. The pilot and validation processes further confirm that these topics were judged relevant to labour-market needs and professional application.

A second implication concerns provider capacity and institutional learning. BESM frames course revision as an iterative process of diagnosis, reflection and redesign, and the digital platform translates this into a usable workflow for providers. This matters because sustainable transitions in construction require not only updated workers, but also adaptive institutions able to revise their training supply as technologies, regulations and labour-market needs change.

7 Conclusion

The BSA represents a significant contribution to the educational dimension of sustainable transitions in the built environment. Its value lies in the way it integrates labour-market intelligence, topical and occupational skills mapping, provider self-assessment, course enrichment, digital support, quality assurance, stakeholder validation and certification logic.

BSA demonstrates that transition priorities such as climate resilience, net-zero construction, circularity, sustainable materials and occupant well-being can be translated into structured and teachable competence frameworks. BESM provides a useful model for provider-level capacity-building by turning course redesign into a systematic rather than ad hoc process. The twelve pilot courses suggest that the model is transferable across countries, EQF levels and thematic domains while still allowing contextual differentiation. Finally, the linkage with quality assurance and certification shows that educational innovation in the built environment should not stop at content reform, but also address trust, transparency and recognition mechanisms.

More broadly, reshaping the built environment requires reshaping the educational infrastructures that prepare those who design, build, maintain and transform it. Awareness, equity, skills and capacity-building are not separate themes, but interdependent dimensions of a common transition process. In this respect, the BSA project provides a persuasive example of how educational innovation can contribute to more resilient, circular and socially responsive futures in construction, while also highlighting the need for further evidence on long-term learner outcomes and scalable uptake beyond the consortium.

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Education for Sustainable Development: (de)constructing the dimensions of awareness regarding the circular economy

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Abstract. Education involves a complex combination of formal and informal approaches and must go beyond traditional methods. To empower young people to think critically, adapt to new technologies, and solve real-world problems, Education for Sustainable Development (ESD) is a crucial approach. In addition, knowledge, skills, and values are relevant concepts that must be directed towards a sustainable future, resulting in smarter, but above all, more responsible choices for the environment, people, and society. Based on the development of moral values and integrity, as well as the respect for social norms, which are crucial for responsible citizenship, this article argues that effective awareness strategies help communities define the character of education. Finally, to evolve from passive to active learning, with the aim of an assertive definition of social marketing strategies, this article develops a literature review to (re)construct the concept of awareness. This is justified because, by promoting awareness campaigns, social marketing can promote environmental responsibility. The main result provides the basis for the construct of awareness and can be used to develop communication strategies associated with the circular economy. In the long term, critical thinking strategies must be part of this process. Finally, it highlights the possibility of digital tools such as artificial intelligence.

Keywords: Awareness · Circular Economy · Education for Sustainable Development · Social Marketing

1 Introduction

Extending the life cycle of materials through continuous circulation, the circular economy (CE) is an approach that transforms a traditional economy into a restorative economy [1]. Consumers were classified as enthusiasts (high commitment to sustainability) and skeptics (low involvement in environmental issues) [2]. However, between these extremes, there are countless intermediate groups.

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Generation Z is known for being more environmentally conscious, and the circular economy has emerged as an attractive alternative [3]. Awareness [1] is important. Nevertheless, the awareness of the circular economy remains low [4]. Through education for sustainable consumption and increased awareness, particularly ethical awareness [5], CE is supported.

Education was considered important for promoting sustainable choices [6]. However, education involves a complex combination of formal and informal approaches and must go beyond traditional methods.

Awareness towards initiatives promoting sustainable practices is increasing [6]. Younger, educated women with strong environmental awareness are the most suitable profile for developing sustainable consumption strategies [3, 4]. New technologies [7] can empower young people to think critically and solve real-world problems [8].

Education for Sustainable Development (ESD) is a crucial approach. In this sense, this research assumes that environmental education and training are important in raising consumer awareness [6], and Social Marketing (SM) can offer communication strategies. Targeted communication strategies and economic incentives [9]. In addition, policy (e.g., taxes), economic (e.g., Gross Domestic Product), social (e.g., education), and technological (e.g., patents) factors can serve as effective policy tools and influence decisions regarding the circular economy [10].

A structured literature review aims to develop the construct of "sustainability awareness" for use in communication strategies to promote more sustainable behaviors associated with the circular economy. This review was conducted in February 2026 using Web of Science databases. The search string included 'awareness', 'circular economy', 'education for sustainable development', and 'social marketing'. Plus, only peer-reviewed articles in English were considered, resulting in 15 relevant publications after screening.

In developing moral values and integrity, as well as respecting social norms, CE should consider that effective awareness strategies help communities define the character of education. Knowledge, skills, and values [11] are relevant concepts that must be directed towards a sustainable future, resulting in smarter, but above all, more responsible choices for the environment, people, and society. It is crucial for environmentally conscious consumers [7].

Even more knowledge is required to propose a business model that transitions from a linear to a circular economy [12]. Public management can introduce additional taxes on incineration and invest in developing technologies to promote recycling, improve education, and raise public awareness, with the aim of developing integrated policy frameworks to advance the circular economy [10]. Aiming to increase circularity in the construction sector, this article argues that raising awareness of sustainability is necessary.

Finally, to evolve from passive to active learning, with the aim of an assertive definition of social marketing strategies, this article develops a literature review to (re)construct the concept of awareness. By promoting awareness campaigns, social marketing can promote environmental responsibility. The CE should be considered essential for promoting more sustainable principles in the construction industry [13], including the adoption of sustainable materials and eco-friendly designs [7].

Despite growing research on circular economy awareness, the literature lacks an integrated framework linking awareness dimensions with Education for Sustainable Development and Social Marketing strategies. This study addresses this gap by conceptualizing awareness as a multidimensional construct.

2 (De)constructing Awareness Regarding the Circular Economy

There are two dimensions of awareness that are relevant to behavior: the theoretical concept and its practical application in social marketing. In this sense, the first step is (De)constructing awareness regarding the circular economy.

2.1 Awareness and Circular Economy

Awareness (political, economic, and environmental) and technological skills were considered important for the development of the CE [14]. In this sense, the theoretical concept of awareness can be structurally useful for promoting CE. Awareness is a cognitive ability associated with perception, but it can also reflect a state of being aware, particularly of thoughts, emotions, and experiences. By manipulating stimulus conditions, awareness can be evaluated [15].

Awareness can be evaluated along a continuum from passive to active consciousness [16]. In other words, awareness may range from basic sensory perception, in which the individual is aware of sensations, to active consciousness, more profoundly, to self-awareness [17], which allows for conscious interaction with the environment and behavioral regulation. Moreover, awareness, as the sense of having a deep and accurate understanding of one's own perceptions and thoughts, self-awareness [17], allows us to recognize one's personality, actions, values, and emotions. A circular mindset and circular awareness significantly affect individuals' propensity for circular behavior [18]. Table 1 gives a summary of awareness.

Table 1. Multidimensional awareness framework for circular economy

Concept of Awareness	Theoretical dimensions
Cognitive ability (passive to active awareness/mindfulness)	Political awareness Economic awareness Environmental awareness Technological awareness

Political Awareness. To raise public awareness about recycling, waste reduction, and the benefits of sustainable practices, it is suggested that educational campaigns be developed (e.g., in schools and communities) [10]. In addition, leadership from government and local authorities should be improved [1].

Economic Awareness. Upcycling as a niche market to be explored [3]. Among the driving factors, the following stand out: i) raising public awareness, ii) efficient use of materials, iii) promoting technological innovation, iv) positioning of companies [12].

Environmental Awareness. Awareness of circular economy concepts [4]. The lack of environmental awareness, as well as the association of recycled goods with lower quality, suggests raising sustainability awareness among digital-native generations [5]. It is suggested that awareness of the benefits of recycling/reuse/refurbishment/repair [1] be increased.

Technological Awareness. Creative recycling [4], efficient use of materials [12], and encouraging research and innovation [10].

Social marketing uses the same principles, techniques, and tools as commercial marketing to promote behaviors that benefit individuals, society, and the environment. Given the relevance of awareness to behavioral science, the next step is to apply the awareness concept in the circular economy to develop Social Marketing communication strategies to promote Education for Sustainable Development (ESD).

2.2 Social Marketing and Education for Sustainable Development

Social marketing can use the same principles and tools as commercial marketing to promote educational campaigns that raise awareness of sustainable development. In Portugal, for example, the rate of circular use of materials (i.e., the percentage of materials recovered and reused in the economy) is quite low. According to Pordata, it stands at just 3%. According to Pordata, only 3%. In addition, Portugal ranked 24th among the 27 EU countries in 2024 [19]. Like Portugal, other European countries can also improve their material utilization rates, as even the Netherlands, which has the highest rate, has not reached 33%. By providing assertive fundamentals to build awareness, social marketing campaigns can be a powerful ally in developing long-term communication strategies for the circular economy.

Segmentation. Groups of individuals with similar preferences that are more inclined to pay for environmentally friendly products. Gender, education, and psychological factors influence behavior; the spectrum ranges from skeptics (low commitment) to enthusiasts (high commitment) [2]. Younger, educated women are the profile of the most receptive segment, as are individuals with environmental awareness [4]. Environmental responsibility and awareness are significant factors in sustainable behavior [2]. Generation Z was identified as the most environmentally aware group [3].

Positioning. Positioning is about delivering value. A left-leaning political orientation was associated with engagement in sustainable practices [2]. In this sense, it is crucial to provide guidance to policymakers but also highlight the benefits and value to other stakeholders, such as companies, always with the aim of promoting CE practices in developing countries, emphasizing the importance of ethical awareness and education to drive sustainability [5]. It is also necessary to consider the values of other stakeholders, such as builders and consultants, located in various organizations throughout the value chain, who must develop practical solutions to mitigate challenges [1]. There is a

potential market for circular economy-certified products that should be explored [6]. In addition, end-of-life strategies (e.g., recycling and repair, or take-back programs) offer sustainable value (by extending product life cycles) [7].

Concept of Product. Tangible and intangible aspects can help describe the product in question. Considering that motivations influence willingness [4], the concept of the product should include benefits in all theoretical dimensions, including environmental. Environmental education is needed to increase consumer preference for these products [6]. The design should be integrated with policy frameworks and enhance education and public awareness to foster circularity [10].

Policy Price. Price is beyond value. Every effort expended can be considered in policy price, as well as payment methods, financing options, cancellation, and changes to purchases. The complexity of circular processes can lead to high costs (e.g., recycling technologies [10] in the reintegration of the material cycle [1].

Policy Distribution. The distribution policy covers the entire supply process, from producer to consumer. Thus, planning and design are important and should be developed before getting started [1]. Management strategies should be process- and market-oriented [12]. Despite the cost, it is suggested to explore new offers with products based on circular economy-certified products [6].

Promotion. Promotion involves the entire, continuous, long-term process, as well as the relationship with the market. Communicating everything is not the main objective. The goal is to help people decide on the best alternative for themselves, for society, and, above all, for the environment. Assertiveness is the keyword. Promotion encompasses the entire process of communication and relationship with the market. Education is important for promoting sustainable choices and certified products [6]. Creating communication strategies [9] is relevant to the communication process. Driving sustainable consumption, ethical awareness, and targeted education are part of the process [5] to promote CE. In this sense, it is suggested to communicate only what is relevant to achieving strategic objectives.

Within this framework, communication strategies grounded in social marketing principles can influence decision-making processes related to the circular economy. Decision-making is a voluntary and cognitive process; it is assumed that awareness is relevant to CE because it increases the likelihood of making the best decision. Drawing on awareness as a cognitive ability for achieving mindfulness, this research aims to (de)construct awareness of the circular economy.

3 Proposal to Increase Awareness of the Circular Economy

Considering the relevance of awareness, to increase awareness regarding ESD to improve CE, social marketing identified the main aspects based on these objectives:

Promoting Political Awareness. Educational campaigns (e.g., in schools, communities, and companies) can help people understand the benefits of sustainable practices (e.g., recycling or waste reduction), raise public awareness, disseminate policies, and

help them become better leaders. Derived from the political awareness dimension, these campaigns can enhance citizens' understanding of sustainability policies and foster leadership engagement.

Promoting Economic Awareness. Social marketing enhances companies' image and trust, thereby improving their positioning. Upcycling can be explored as a niche, as well as the efficiency of materials and technological innovation.

Promoting Environmental Awareness. Considering the lack of environmental awareness and the association of recycled goods with lower quality, raising sustainability awareness is relevant. Campaigns help educate about sustainability, increase awareness of the benefits of recycling/reuse/refurbishment/repair, and inform people about the quality of recycled goods.

Promoting Technological Awareness. Engagement is a social marketing objective that encourages innovation and promotes creative recycling and the efficient use of materials. Creative recycling, efficient use of materials, and innovation should be encouraged.

In this sense, social marketing can explore educational models (i.e., gamification) combined with technologies (i.e., digitalization), which can be very helpful to promote a sustainable way of thinking [20], as well as to be used by the communication strategy.

4 Final Considerations

To promote awareness campaigns, it became necessary to shift from passive to active awareness and learn from previous results. Based on the (re)construction of the concept of awareness, the objective of this research was to (de) construct awareness regarding the circular economy to assertively define a basis for communication strategies in the field of social marketing.

It is crucial to define the segment(s) to communicate and the respective value(s) to deliver, as well as the tangible and intangible aspects of the products, including benefits, the pricing (effort) and distribution (supply) policies to communicate well (promotion), and develop the promotion strategy.

Social Marketing provides the basis for the construct of awareness and can be used to develop communication strategies associated with the circular economy. In the long term, critical thinking strategies must be part of this process. Finally, it highlights the potential of Education for Sustainable Development, using digital tools such as artificial intelligence to improve outcomes.

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Sustainable Innovation in the Wood Value Chain

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Abstract. The transition to climate-resilient and resource-efficient industries is increasing global interest in regenerative, bio-based, and composite materials. In this context, the wood value chain presents significant opportunities to reduce embodied energy, lower whole-life carbon emissions, and enhance circular material flows. Advances in wood-derived composites, renewable biopolymers, and secondary raw materials generated through industrial symbiosis show how bio-based innovation can replace fossil-based materials while supporting long-term carbon storage. These developments are particularly relevant for Slovenia, where forest resources remain underutilised, and the potential for sustainable value creation is considerable. This paper synthesises the work of Master's students in Wood Science and Technology, who examined innovation across the forest–wood value chain through the lens of the United Nations Sustainable Development Goals. Their analyses provide a structured overview of how emerging materials, improved resource management, and circular business models contribute to climate mitigation, biodiversity protection, and more resilient industrial systems. By integrating sustainability concepts with practical examples from the wood sector, the students highlight the importance of evidence-based decision-making and the need for future professionals to combine technical expertise with an understanding of socio-environmental impacts. This work contributes by systematically mapping Sustainable Development Goal-related innovation opportunities within a single sector, showing how targeted interventions in material design, resource sourcing, and process optimisation can advance sustainability out-comes. The study also highlights the value of accessible analytical tools, such as life-cycle perspectives, comparative assessments, and basic digital monitoring, in supporting informed and responsible practice. Together, these insights illustrate the broader role of the wood value chain in advancing a sustainable, low-carbon bioeconomy.

Keywords: Bio-Based Materials · Circular Economy · Lifecycle Assessment · Wood Value Chain · Whole-Life Carbon · Sustainable Innovation

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1 Introduction

The forest–wood value chain is central to the transition to a climate-resilient and resource-efficient bioeconomy. As a renewable, locally available raw material, wood can replace emission-intensive materials in construction, packaging, furniture, and various bio-based products, while storing biogenic carbon and supporting rural employment. However, increasing demand for biomass and wood-based materials poses risks to forest ecosystems, biodiversity, and social equity if not governed by robust sustainability criteria [1–3].

The United Nations 2030 Agenda for Sustainable Development [4] highlights these tensions and opportunities across multiple Sustainable Development Goals (SDGs). Within this framework, this paper synthesises the work of Master's students in Wood Science and Technology, who analysed the links between the wood value chain and individual SDGs, focusing on sustainable innovation pathways in forests, wood processing, biomass utilisation, and bio-based materials. Each student addressed one SDG, examining its relevance to the wood sector, innovation levers, case studies, challenges, and policy recommendations. The SDGs covered range from Zero Hunger (SDG 2) and Good Health and Well-being (SDG 3) to Gender Equality (SDG 5), Clean Water and Sanitation (SDG 6), Affordable and Clean Energy (SDG 7), Decent Work and Eco-nomic Growth (SDG 8), Industry, Innovation and Infrastructure (SDG 9), Reduced In-equalities (SDG 10), Sustainable Cities and Communities (SDG 11), Responsible Consumption and Production (SDG 12), Climate Action (SDG 13), Life Below Water (SDG 14), Life on Land (SDG 15), Peace, Justice and Strong Institutions (SDG 16), and Partnerships for the Goals (SDG 17).

The aim of this contribution is not to present fifteen separate case studies, but to integrate them into a coherent analysis of how sustainable innovation in the wood value chain can contribute to multiple SDGs simultaneously, identifying where synergies emerge, and where trade-offs and risks must be managed. In doing so, the paper links students' SDG-specific insights with broader European policy frameworks such as the EU Forest Strategy [5], the EU Bioeconomy Strategy [6], and the Circular Economy Action Plan [7], as well as evolving requirements for ESG reporting and lifecycle-based assessment.

2 Methodological Approach

The analysis in this paper is based on fifteen SDG-focused chapters prepared by Master's students of Wood Science and Technology at the Biotechnical Faculty, University of Ljubljana, using a common assignment template. Each chapter included: (i) an introduction to the SDG and its global context; (ii) the relevance of the SDG to the forest–wood value chain; (iii) sustainable innovation levers grouped into technological, business model, social/organisational, and policy/certification dimensions; (iv) case studies and examples; (v) key challenges, trade-offs, and risks; and (vi) recommendations for practice and policy, followed by conclusions.

For this integrated paper, the chapters were synthesised qualitatively. The synthesis reflects the structure of the original assignment and the diversity of student perspectives, while distilling key patterns relevant to research, education, and practice in sustainable wood value chains.

3 Results: SDG Perspectives on the Wood Value Chain

3.1 Environmental and Resource-Oriented SDGs (2, 6, 7, 11, 12, 13, 14, 15)

Several SDGs emphasise environmental protection, circular resource use, and climate mitigation, all of which are closely linked to forest ecosystems and wood-based industries [8]. SDG 2 (Zero Hunger) highlights the role of forests in food security through non-wood forest products and ecosystem services that support agriculture, such as soil protection, water regulation, and climate buffering. Innovation pathways include fungal biotechnology, mycelium-based systems using wood residues as substrates, and agroforestry models that integrate trees, crops, and livestock to enhance resilient food systems [9].

SDG 6 (Clean Water and Sanitation) highlights forests as natural regulators of hydrological cycles and notes the high water use of certain wood-processing sectors, especially pulp and paper. Technological innovations such as closed-loop water systems, advanced wastewater treatment, and bio-based process chemicals, along with industrial symbiosis and nature-based solutions in catchment management, can significantly re-duce water abstraction and pollution [10].

SDG 7 (Affordable and Clean Energy) identifies sustainably sourced wood biomass as a renewable energy carrier that can enhance local energy security, especially when residues and low-value streams are prioritised. Innovations in high-efficiency combustion, combined heat and power, modern biomass boilers, and digital energy monitoring are supported by governance measures that prevent conflicts between the material and energy use of wood and avoid excessive pressure on forest ecosystems [11].

SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production) converge on sustainable construction, circular material flows, and urban–forest linkages. Engineered wood products such as cross-laminated timber (CLT) and adhesive-free building systems enable low-carbon, resource-efficient buildings, while circular business models in furniture and urban infrastructure reduce waste and extend product lifetimes [11]. Company examples such as iQwood, Stilles, Lumar, M Sora, Binderholz, and projects like WoodInnovate demonstrate how cascading use of wood, certified sourcing, and design for longevity put SDGs 11 and 12 into practice. SDG 13 (Climate Action) connects many of these themes by presenting forests as car-bon sinks and wood products as long-lived carbon stores that can replace emission-intensive materials [12]. The student analyses highlight the importance of engineered timber, climate-smart forestry, cascading biomass use, digital monitoring of forest health and carbon stocks, and climate-oriented business models, including carbon cred-its. They also note the risks of overharvesting, carbon leakage, and greenwashing if bio-based solutions are implemented without robust lifecycle assessments and transparent reporting.

Although SDG 14 (Life Below Water) focuses on marine ecosystems, analyses show that forestry and wood processing affect downstream water bodies through erosion, nutrient runoff, and effluents. Water stewardship, advanced wastewater treatment, and bio-based substitution for plastics in packaging reduce land-based sources of marine pollution [13, 14]. Case studies from companies such as Billerud and UPM demonstrate measurable commitments to reducing effluents and protecting watersheds.

Finally, SDG 15 (Life on Land) is closely linked to the wood value chain, given its focus on forest conservation, land degradation, and biodiversity [15, 16]. The student work emphasises that the climate and material benefits of wood depend critically on sustainable forest management, protection of primary and old-growth forests, and careful balancing of harvesting levels with ecosystem resilience. Technological innovations such as nanocellulose and wood-based 3D printing can reduce dependence on fossil materials, while business models such as cooperatives and FSC-certified value chains demonstrate how terrestrial biodiversity protection can be combined with economic development [9].

3.2 Social and Labour-Oriented SDGs (3, 5, 8, 10, 16)

SDG 3 (Good Health and Well-being) links health outcomes with forest loss, occupational exposures in wood processing, and indoor environmental quality [17]. Students highlight the impacts of deforestation on microclimates and disease risks, the need to minimise workers' exposure to wood dust, volatile organic compounds (VOCs), and formaldehyde, and the potential for low-emission materials and timber interiors to sup-port healthier indoor environments. Innovations such as adhesive-free engineered wood products are identified as promising for reducing chemical emissions during both pro-duction and use.

SDG 5 (Gender Equality) highlights the persistent under-representation of women in forestry and wood industries, especially in physically demanding and technical roles [17]. The analysis indicates that technological innovation to reduce physical strain, targeted educational measures, and company policies on equal pay, promotion, and participation in decision-making are key levers for change. National legal frameworks on non-discrimination provide an important enabling context but require complementary organisational innovation.

SDG 8 (Decent Work and Economic Growth) focuses on improving productivity and working conditions while avoiding environmentally harmful growth strategies. In the wood value chain, this includes addressing hazardous forestry operations, informal employment, and unequal value distribution along global supply chains [19]. Students highlight the importance of circular business models, local and regional value chains, skill development, and integrated sustainability assessments that combine economic, social, and environmental indicators.

SDG 10 (Reduced Inequalities) highlights regional disparities and unequal access to innovation and markets across the forest–wood value chain. Rural and peripheral regions where forestry is concentrated often lack high-value processing capacity and digital infrastructure [20]. Advanced biomaterials, digital forestry, and decentralised additive manufacturing can help upgrade regional industries, provided investment barriers for small and medium-sized enterprises (SMEs) are addressed and inclusive business models, such as cooperatives and industrial symbiosis, are promoted.

SDG 16 (Peace, Justice and Strong Institutions) emphasises the importance of transparent, accountable governance in combating illegal logging, corruption, and labour rights violations [21]. The analyses highlight the role of traceability systems, digital monitoring, robust certification, and Green Public Procurement in strengthening the rule of law and public trust. They also stress that fair working conditions, gender equality,

and participatory governance in the wood sector are integral to SDG 16, not secondary issues.

3.3 Industrial Transformation and Partnerships (9, 17)

SDG 9 (Industry, Innovation and Infrastructure) is directly linked to the modernisation of forest-based industries through advanced wood materials, digitalisation, and circular business models [22]. The student analysis demonstrates how engineered timber, mycelium-based composites, Forest 4.0 approaches, and industrial symbiosis can reduce whole-life emissions, increase resource efficiency, and create high-quality jobs in rural regions, while warning of a potential 'biomass gap' between demand and sustainable supply [22].

SDG 17 (Partnerships for the Goals) incorporates many of the above themes by emphasising multi-stakeholder collaboration, knowledge and data sharing, and financing mechanisms [23, 24]. In the forest–wood context, this includes EU Forest Partnerships, science–business platforms, forest cooperatives, and cross-border research projects under Horizon Europe. Certification schemes, Green Public Procurement, Environmental Product Declarations, and environmental, social and governance (ESG) frameworks serve as partnership infrastructures that coordinate expectations and data flows across governments, companies, researchers, and civil society.

4 Discussion

The integrated analysis of the student SDG chapters reveals a highly interconnected landscape of opportunities and risks for the wood value chain. On the opportunity side, forests and wood-based materials can contribute simultaneously to climate mitigation, circularity, rural development, healthy buildings, food security, and social inclusion, provided that sustainable forest management, innovative materials, and circular business models are combined with robust governance and inclusive labour practices.

At the same time, the students highlight several structural tensions. These include trade-offs between increasing biomass demand and safeguarding biodiversity and carbon sinks; between short-term economic growth and long-term ecosystem resilience; and between the narrative of 'green' materials and the risk of greenwashing if claims are not supported by reliable data or credible assessments. Another cross-cutting issue is inequality: between rural and urban regions, small and large companies, and different social groups within the workforce. While the bioeconomy is often presented as an opportunity for inclusive growth, the students' work suggests that without targeted support for SMEs, small forest owners, women, and vulnerable groups, innovation may reproduce or even exacerbate existing inequalities.

Importantly, the seminar-based approach has educational value in itself. By engaging directly with SDG frameworks, policy documents, and case studies, students demonstrate how future professionals in wood science and technology can develop systems thinking, understand multi-dimensional sustainability trade-offs, and relate their technical expertise to broader societal goals. This highlights the role of higher education as a catalyst for SDG-aligned innovation in the wood value chain.

5 Conclusions

This paper synthesised fifteen SDG-focused analyses prepared by Master's students to explore how sustainable innovation in the forest–wood value chain can contribute to the 2030 Agenda (see Fig. 1). Across environmental, social, economic, and governance dimensions, the results show that wood-based solutions can play a significant role in advancing SDGs on climate action, responsible consumption and production, sustainable cities, decent work, reduced inequalities, healthy environments, biodiversity, and effective institutions.



Fig. 1. Integration of sustainability opportunities within the wood value chain mapped against the Sustainable Development Goals.

However, these contributions are conditional. They depend on sustainable forest management that respects ecological limits, lifecycle-based assessments that avoid burden-shifting and greenwashing, inclusive business models and labour practices that reduce rather than exacerbate inequalities, and policy and certification frameworks that are both ambitious and accessible to smaller actors.

From an educational perspective, the seminar demonstrates the value of SDG-based project work in training future professionals to integrate technical knowledge with systemic sustainability thinking. For researchers, companies, and policymakers in the wood sector, the students' work indicates a research and innovation agenda that com-bines advanced bio-based materials, digitalisation, circular business models, social inclusion, and strong institutions as mutually reinforcing pillars of a sustainable, resilient, and just forest-based bioeconomy.

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How to Integrate the Gender Dimension into the Research of Simulation Tools and Sustainable Insulation Materials to Achieve Zero-Emission Buildings

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Abstract. The objective of this study is to analyse and integrate the gender dimension into the research activities of the SNUG Horizon Europe project, which focuses on circular economy-based material development for sustainable, high-energy performance buildings. The study addresses two research questions: which building component characteristics promote equitable workforce participation and which indoor environment attributes are disproportionately prioritised by women as occupants. A narrative literature review was conducted across ergonomics, gender studies in construction, and indoor environmental quality, followed by an analytical review of SNUG project deliverables and activities. Results reveal that lightweight materials, modular systems, and technically sophisticated installation processes reduce physical barriers to workforce participation, while superior thermal performance and indoor air quality directly address women's documented sensitivity to thermal comfort and air quality as occupants. A three-tier framework for gender integration across the SNUG research lifecycle is proposed, encompassing structural, analytical, and translational dimensions. The study concludes that the SNUG project's technical achievements position it as a reference for gender-responsive sustainable construction innovation, contingent on systematic implementation of the proposed recommendations across data management, digital tools, demonstration actions, and communication strategies.

Keywords: Thermal Insulation · Construction · Material · Specification · Gender · Indoor Environmental Quality · Workforce Inclusion · SNUG Project

1 Introduction

The construction sector is one of the largest contributors to global energy consumption and greenhouse gas emissions and is simultaneously characterised by persistent gender disparities in both its workforce and its built outcomes. Women remain significantly

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underrepresented in construction occupations, particularly in site-based and technical roles, while also being documented as disproportionately affected by indoor environmental quality as building occupants due to physiological, metabolic, and behavioural differences [1, 2, 13, 14]. The transition toward sustainable, zero-emission buildings therefore presents a dual opportunity: to redesign construction materials and processes in ways that reduce physical barriers to workforce participation, and to optimise building performance for the full diversity of occupants.

The SNUG Horizon Europe project ("Circular Economy Based Materials Development to Foster The Transition to Sustainable and High-Energy Performance Buildings at Optimal Costs"; https://snugproject.eu/) has developed a portfolio of innovative construction materials including lightweight bio-based panels, aerogel-enhanced plasters, self-levelling mortars with phase change materials, and aerated eco-concrete blocks. These materials offer documented advantages in thermal performance, embodied carbon reduction, and installation ergonomics. However, their potential to advance gender equity, both for workers and occupants, has not been systematically examined, nor has a structured framework been proposed for integrating the gender dimension across the SNUG research lifecycle.

Despite EU mandates for gender mainstreaming in Horizon Europe programmes, systematic integration of gender dimensions in construction research remains limited [2, 7, 8]. Existing studies tend to address either workforce inclusion or occupant comfort in isolation and rarely connect material innovation to both dimensions simultaneously. This gap is particularly significant for sustainable construction research, where the social and environmental dimensions of innovation are increasingly recognised as inseparable.

This paper addresses two interrelated research questions: (1) Which building component and material characteristics promote equitable participation of all genders in construction work by reducing physical barriers and improving working conditions? (2) Which indoor environment attributes are disproportionately prioritised by women as occupants due to physiological, metabolic, and time-use differences? Building on the answers to these questions, the paper proposes a comprehensive, actionable framework for integrating the gender dimension into the SNUG project's ongoing research, development, and communication activities.

2 Method

This study employs a two-stage methodology. The first stage consists of a narrative literature review addressing the two research questions identified in the Introduction. The second stage comprises an analytical review of SNUG project deliverables, activities, and material performance data, from which gender-responsive recommendations are derived and a structured integration framework is proposed.

2.1 Narrative Literature Review

A narrative literature search was conducted across Scopus, Science Direct, and Google Scholar to identify studies relevant to gender dimensions in construction workforce participation and indoor environmental quality. Sources were selected on the basis of direct

relevance to the two research questions; 28 peer-reviewed publications are referenced in this paper. The review does not claim exhaustiveness and does not constitute a formal systematic review or meta-analysis; its purpose is to identify the principal evidence threads that inform the analytical framework.

2.2 Analytical Review of SNUG Project Activities

The second methodological component involved a structured review of SNUG project deliverables, technical reports, and work package documentation available at the time of writing. Material performance data, including density, thermal conductivity, VOC classification, and installation characteristics, were extracted and evaluated against the gender-relevant criteria identified in the literature review. Specific items reviewed include: the Data Management Plan, the Digital Tool Assistant building simulation software, the Digital Building Logbook data model, stakeholder engagement protocols, and communication and exploitation strategies. For each item, gaps in gender integration were identified and targeted recommendations were formulated. A three-tier theoretical framework for gender mainstreaming across the research lifecycle was developed inductively from this process.

3 Results

3.1 Building Component Characteristics Promoting Workforce Inclusivity

Physical demands and workplace design are significant barriers to equitable participation of all genders in construction work. Women are often required to perform physically demanding tasks such as digging and lifting, which can be particularly challenging due to differences in average physical capacity and the absence of work division based on ability rather than gender. This leads to undue physical stress and increased injury risk, compounded by the absence of adequate sanitary and welfare facilities for women on many construction sites [1–4].

Lightweight materials, including lightweight concrete, engineered cementitious composites, composite panels, and foam concretes enhanced with biobased admixtures, significantly reduce the dead load of building elements, making them easier to handle, transport, and install. This weight reduction directly lessens physical strain, offering a critical ergonomic advantage for tasks involving repetitive lifting, carrying, or assembly, while accommodating a broader range of physical capabilities and reducing the risk of work-related musculoskeletal disorders. Beyond individual ergonomic benefits, lightweight thermal insulation materials support wider workforce inclusion by lowering physical barriers to participation, enabling cost savings in transportation and training, and aligning construction practice with sustainable and circular economy principles [5, 6].

Workplace culture and organisational practices represent an equally significant dimension. The construction industry's strong masculine culture often manifests as exclusionary behaviours, gender discrimination, harassment, and limited access to skilled positions for women, compounded by the absence of gender-sensitive policies [2,

7–10]. Long and inflexible working hours disproportionately affect women with caregiving responsibilities; reducing work hours and promoting flexible scheduling are necessary but require industry-wide collaboration [2, 9, 11]. Tailored safety training, mentorship systems, and supervisor support are associated with higher job satisfaction and reduced gender-based harassment and represent actionable organisational interventions that complement material-level improvements [1, 10, 12].

3.2 Gender Differences in Indoor Environment Preferences

Women are generally more sensitive to deviations from optimal thermal environments and express higher dissatisfaction, especially in cooler conditions. This increased sensitivity is attributed to lower metabolic rates, differences in body composition, and hormonal influences; optimal temperature ranges for women are documented as higher than for men (18.5–24.2 °C vs. 17.3–23.4 °C) [13–17]. As a result, thermal comfort and indoor air quality (IAQ) are disproportionately prioritised by women, who report higher dissatisfaction even after controlling for psychosocial and occupational factors [15, 18, 19].

Women typically spend more time indoors and engage in more in-home activities, increasing their exposure and sensitivity to indoor environmental quality factors such as lighting, air quality, and thermal comfort [20, 21]. Energy-related behaviours also differ by gender: women more frequently use air conditioning and cooling devices, reflecting higher demand for thermal comfort [21]. Women also place greater importance on building security, cleanliness, and maintenance characteristics, which feature more prominently in their post-occupancy evaluations [22]. Building material choices directly affect women's respiratory health: persistent dust, poor ventilation, and indoor air pollution are significant risk factors, further emphasising the importance of low-emission materials in environments where women spend substantial time [23].

3.3 Gender-Responsive Properties of SNUG Materials

Retrospective analysis of SNUG material performance data identifies twelve characteristics with gender-relevant implications. Workforce inclusion facilitators include weight and density reduction (bio-panels at 290 kg/m^3); installation speed and simplicity; on-site adaptability and cuttability; mechanical robustness reducing unit handling requirements; dimensional stability minimising corrective work; and maintenance ease reducing physically demanding repairs. Occupant health benefits encompass: thermal insulation addressing women's higher comfort temperature requirements (24.2 °C vs. 23.4 °C) [24, 25]; indoor air quality improvements for populations showing greater sick building syndrome prevalence among women; low VOC emissions (A+ classification, 21–31 ppb formaldehyde); fungal resistance protecting vulnerable populations; sound insulation addressing acoustic sensitivity; and low dangerous substance release during fire events [26–28].

4 Discussion

4.1 Proposed Theoretical Framework for Gender Integration

The results of the literature review and the retrospective material analysis converge on the need for a structured, multi-level approach to gender mainstreaming in sustainable construction research. A three-tier framework is proposed. Tier 1 (Structural Integration) embeds gender in the foundational research structure, including data models, metadata standards, and monitoring systems. Tier 2 (Analytical Integration) incorporates gender-differentiated parameters into methodologies through material selection criteria, thermal comfort algorithms, and user requirement specifications. Tier 3 (Translational Integration) communicates gender dimensions through sex-disaggregated analyses, business cases, and policy briefs. This framework extends beyond binary sex categories to examine intersections with age, disability, socioeconomic status, and cultural background, recognising that gender-responsive design serves broader accessibility and social equity objectives.

4.2 Proposed Operational Recommendations for the SNUG Project

The Data Management Plan should incorporate gender commitments through mandatory metadata fields capturing gender identity (with non-binary options), age, socioeconomic indicators, and occupant demographics across all survey datasets. FAIR Principles alignment should include gender-related keywords for findability and standardised gender taxonomies (ISO/IEC 5218 extended) for interoperability. A Gender Dimension Monitoring Dataset should track a set of key performance indicators, including women in project roles, PhD graduates, researchers, management positions, publications, patents, and outreach participation, with quarterly updates.

Future material specifications should explicitly incorporate gender-responsive criteria, with selection matrices weighting characteristics by social impact alongside environmental and economic performance. The Digital Tool Assistant (DTA) should integrate gender-differentiated thermal comfort models (e.g., 50% female occupancy increases optimal temperature by 0.4 °C), demographic specification fields in the user interface, and "comfort equity" as an optimisation criterion alongside energy efficiency. The Digital Building Logbook (DBL) data model should be extended with occupant demographic fields, gender-disaggregated energy consumption tracking, and social equity indicator categories, with explicit policy alignment to the EU Gender Equality Strategy and ISO 26000.

Demonstration projects should deliberately recruit diverse installation teams and use ergonomic feedback from workers with varied physical capabilities to refine material design, packaging, and training protocols. Communication and exploitation strategies should integrate a "Women in Sustainable Construction" series and social impact briefs for each exploitable result, with gender-balance monitoring for conferences and social media. At least 7% of publications should address gender dimensions, and gender integration toolkits should be developed for future construction research programmes.

4.3 Limitations

This study is analytical and framework-oriented rather than empirical. No primary data on workforce composition, ergonomic outcomes, or occupant satisfaction were collected for SNUG materials specifically, and the gender-responsive properties identified in Sect. 3.3 are based on retrospective analysis of technical performance data rather than field studies with gender-disaggregated outcomes. Physical demands and thermal sensitivity moreover represent only two dimensions of a complex system: harassment, discrimination, inflexible scheduling, and pay inequity are frequently cited as more significant barriers to women's participation in construction [2, 7, 9], and the framework proposed here cannot address these structural factors through material innovation alone. Empirical validation through gender-disaggregated field trials, worker surveys, and occupant studies is required to substantiate the theoretical connections proposed in this paper.

5 Conclusions

The SNUG project's lightweight materials, superior indoor air quality, and excellent thermal performance represent genuine technical advances with significant, if as yet unvalidated, potential for gender-responsive impact. The literature review confirms that lightweight and ergonomically optimised materials reduce physical barriers to workforce participation, while superior thermal insulation and low VOC emissions directly address women's documented sensitivity to thermal comfort and indoor air quality as occupants.

The three-tier framework and operational recommendations proposed in this paper provide a comprehensive and actionable pathway for translating SNUG's technical achievement into social intentionality. Implementation requires minimal additional resources while enhancing social impact and EU policy compliance. The recommendations recognise that gender-responsive research is not about adding constraints but expanding possibilities: construction innovation that serves diverse workers and varied occupants simply performs better. With targeted interventions in demonstration actions, digital tool development, data management, and communication strategy, SNUG can become a reference for gender-responsive sustainable construction innovation in the Horizon Europe programme.

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Circular Economy for Climate Change Mitigation: Factors Influencing Citizens' Awareness

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Abstract. Scientific evidence underscores the need to adopt a circular economy model in the construction sector to mitigate climate change, with awareness being a crucial enabler. Socioeconomic factors influencing the adoption of circular economy practices represent a significant but underexplored area of research. In this aspect, this study examines citizens' perceptions of the circular economy and climate change, as well as investigates the socioeconomic factors affecting citizens' awareness through a quantitative survey conducted in nine European countries (Denmark, Germany, Greece, Italy, Poland, Portugal, Romania, Spain, and the UK). The survey, focusing on citizens' awareness and behaviour towards the circular economy in the construction sector, was carried out in December 2023, involving approximately 500 participants per country (4,512 in total). Descriptive statistics were used to reveal citizens' perceptions, while regression models were used to identify the factors influencing citizens' awareness. The analysis showed that citizens are highly aware of climate change mitigation, and not relatively aware of the circular economy. Regression models revealed that citizens' awareness depends on factors such as age, education level, relevant work experience, and environmental concerns. This research aims to contribute to understanding citizens' perceptions to develop targeted strategies that will lead to a more sustainable built environment.

Keywords: circular economy · citizens · awareness · factors · construction sector · climate change

1 Introduction

The adoption of circular economy (CE) principles is considered important for achieving sustainability and environmental goals, including carbon neutrality by 2050, set by the European Union [1, 2]. Although CE awareness is regarded as a key enabler towards

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circularity, there is an acknowledged lack of empirical studies that systematically examine the socioeconomic factors influencing CE awareness [1, 3, 4]. The limited existing research on the socioeconomic factors affecting CE awareness arises from the lack of consistent and reliable tools and data for measuring climate change awareness, which limits the ability to conduct comprehensive surveys [1, 5]. Moreover, the existing research has focused mostly on the organisational, governmental, or technical aspects of CE adoption, while giving less attention to citizen awareness and the impact of socioeconomic factors [1].

In this context, this study addresses the abovementioned research gaps by conducting an empirical survey to investigate the citizen perceptions and awareness on CEand climate change mitigation and the socioeconomic factors that affect citizens' awareness. Emphasis is given on the construction sector, since this sector is a significant CO_2 contributor [6, 7].

According to the comprehensive framework developed by Potting et al. (2017) [8], CE strategies can be classified into ten "R" strategies - ranked from highest to lowest circularity - namely: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover. This research also examines citizen perceptions for each of the above R strategies.

The structure of the manuscript consists of 4 Sections. Section 1 introduces the research topics, identifies the gaps; Sect. 2 outlines the research methodology; Sect. 3 presents the research results and discusses the implications; and Sect. 4 concludes the paper.

2 Materials and Methods

To examine citizens' awareness and behaviour regarding the CE and climate change, a quantitative survey was conducted, focusing on citizens' awareness, perceptions, attitudes, and behaviours in the construction sector. To this end, a questionnaire was developed, including the following sections: socioeconomic characteristics; residence characteristics; knowledge and awareness; information box; sharing spaces perceptions; repair/refurbish attitudes; recycle/reuse/refuse attitudes; willingness to pay perceptions; perceptions/attitudes/behaviour on CE construction products. The survey was developed in the framework of the European project CO2NSTRUCT [9]. It was conducted in December 2023 and targeted citizens of nine EU countries (Denmark, Germany, Greece, Italy, Poland, Portugal, Romania, Spain, and the United Kingdom), with approximately 500 participants per country (4,512 in total). The sample was representative of the participating countries' populations in terms of gender, age, and region of residence, and was collected by the "Opinion Poll" survey company via an online, structured questionnaire. The questionnaire was developed in English and translated into all other countries' languages.

Statistical analyses were carried out using SPSS 20 software. Microsoft Excel was used to create the figures in this study. The analysis was realised for the overall sample. Descriptive statistics were used to analyse and present the citizens' profile, and their perceived awareness of the CE (concept and practices) and climate change mitigation. Linear regression models were developed to investigate the factors influencing

citizens' awareness. Specifically, three regression models were created, with CE, climate change mitigation, and CE practices awareness (R_{total}) as the dependent variables, respectively. The independent variables in all models were the respondents' demographic and socioeconomic characteristics, as well as their environmental concerns.

This study analyses and presents survey results on respondents' perceived knowledge and awareness, and investigates the determinants influencing citizens' awareness of CE and climate change mitigation.

3 Results

3.1 Descriptive Statistics

The respondents' profiles were examined using descriptive statistics. The nine countries (Denmark, Germany, Greece, Italy, Poland, Portugal, Romania, Spain, and the United Kingdom) are equally represented, with each accounting for about 11% of the overall sample (i.e., approximately 500 participants per country, for a total of 4,512). Table 1 presents the demographic and socioeconomic characteristics of the survey participants. Most respondents live in urban areas (63%). Male participants represent 47% of the sample. The mean age of the respondents is 42 years old. The most common educational level among respondents is vocational training (35%), and most participants in the survey are currently employed (59%). The majority of respondents (80%) have no prior or current experience in the field of circular economy, environment, or energy. Regarding income satisfaction, the majority of the sample is satisfied (56% agree they are satisfied). Regarding respondents' political ideology, the most common response was "Neither left nor right" (42%) on a left-right scale. Finally, the majority of respondents reported being very concerned about the environment (32% at the maximum level, "7").

The main objective of this research is to investigate citizens' levels of awareness of CE and climate change mitigation. In this regard, the respondents were asked two types of questions. Firstly, they were asked to indicate their perceived level of knowledge on a 7-point Likert scale (Fig. 1). As shown in Fig. 1, most respondents reported low levels of self-perceived knowledge of CE (47% reported "3" or lower), while high levels of self-perceived knowledge of climate change mitigation (48% reported "5" or higher).

Moreover, the survey examined participants' awareness of CE practices by assessing their level of awareness for each of the ten "R" practices. To this context, respondents were asked to indicate which of the ten "R" practices they recognised. As illustrated in Fig. 2, the most widely recognised CE practices are recycling (61%), reuse (55%), and repair (52%), while the least recognised are refuse (16%) and rethink (28%). Based on the responses to this question, a new variable, "CE practices awareness" (R_{total}) was created to reflect the aggregated awareness of the 10 "R" practices. The new variable was calculated as the sum of positive (i.e. "Yes") responses to the individual CE "R" practices, with values ranging from 0 (i.e., no practices were recognised) to 10 (i.e., all 10 "R" practices were recognised).

3.2 Regression Models

To examine the factors influencing citizens' awareness, three linear regression models were developed. Table 2 presents the results of the regression models examining the

Table 1. Respondents' profiles

		Value
Location of residence	Urban	63%
	Suburban	21%
	Rural	16%
Gender	Male	47%
	Female	53%
	Other	0%
Age	Mean	42.36
	Std. Dev.	12.45
	Median	41
Education level	Lower than vocational training	15%
	Vocational training degree	35%
	University/University college degree	30%
	Master degree	17%
	PhD degree	3%
Occupation status	Self-employed	14%
	Employed	59%
	Not working	27%
Relevant to the CE working experience	Yes	20%
	No	80%
Income satisfaction	Strongly disagree	7%
	Disagree	9%
	Slightly disagree	13%
	Neither agree nor disagree	15%
	Slightly agree	21%
	Agree	24%
	Strongly agree	11%
Political ideology	Extremely left	3%
	Left	7%
	Slightly left	16%
	Neither left nor right	42%
	Slightly right	20%
	Right	8%

(*continued*)

Table 1. (*continued*)

		Value
	Extremely right	4%
Environmental concerns	1 (Not at all)	1%
	2	2%
	3	4%
	4	16%
	5	18%
	6	27%
	7 (A lot)	32%

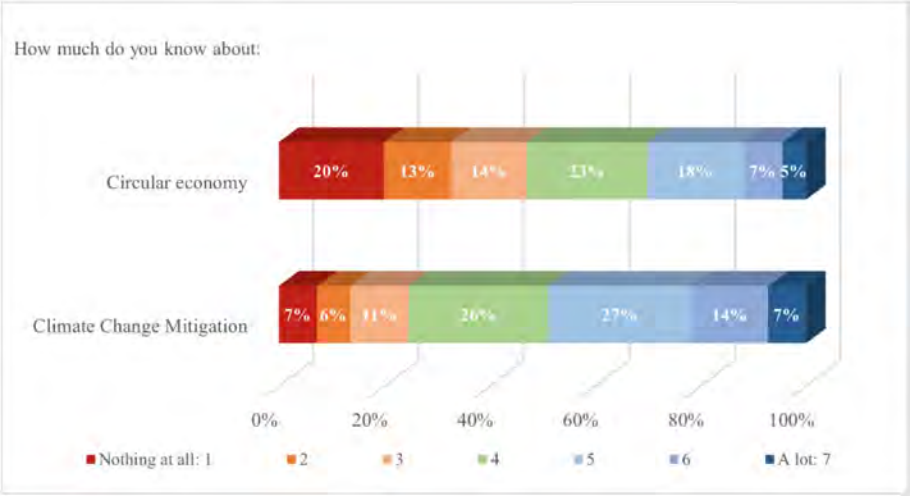


Fig. 1. Self-perceived knowledge of CE and Climate change mitigation

factors influencing participants' awareness of the concepts of CE, climate change mitigation, and CE "R" practices (R_{total}). The independent variables are the same in all models, including sociodemographic characteristics and environmental concerns. The determinants that were identified as statistically significant to at least one model are indicated in Table 2 in "bold" font. The model didn't identify any multicollinearity among the predictor variables (Variance Inflation Factor - VIF), and also no autocorrelation was detected in the residuals of any of the three regression models (as verified by the VIF and Durbin-Watson in Table 2).

The first two regression models, which examine respondents' awareness about the CE and climate change mitigation (dependent variables), yield quite similar results. Based on the results presented in Table 2, the models indicate that, on statistically significant level, respondents living in urban area, of younger age, having a higher

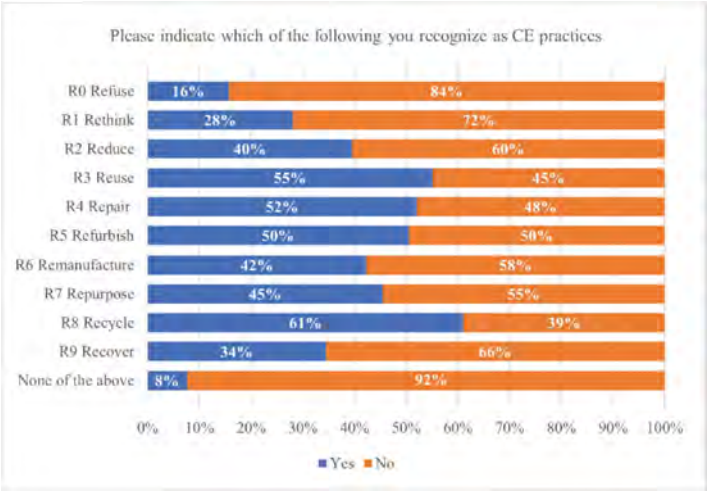


Fig. 2. Respondents' awareness of each "R" practice

education level, who are currently working, with higher income, obtaining relevant CE working experience, with more right-leaning political self-positioning and with higher environmental concerns, are having higher awareness on the concept of CE and climate change mitigation. Specifically, for the second model on climate change mitigation, an additional determinant is gender, showing that, on statistically significant level, males have a higher level of awareness of climate change mitigation.

The third regression model examines respondents' awareness of CE "R" practices (dependent variable). Based on the results, presented in Table 2, the model signifies that, on statistically significant level, respondents of younger age, with higher education level, who don't have relevant to CE working experience, with more left-leaning political self-positioning and with higher environmental concerns, are aware of a larger number of CE "R" practices.

Table 2. Results of regression models on citizens' awareness

	CE awareness	Climate change mitigation awareness	CE practices awareness (R_{total})
	B Pvalue indicator	B Pvalue indicator	B Pvalue indicator
(Constant)	−0.815	−0.244	−0.129
Location of residence (urban)	**0.362** ***	**0.286** ***	0.059
Location of residence (rural)	0.117	0.045	0.049
Gender (male)	0.071	**0.071** *	0.132
Age	**−0.005** ***	**−0.002** ***	**0.014** ***

(*continued*)

Table 2. (*continued*)

	CE awareness	Climate change mitigation awareness	CE practices awareness (R_{total})
Education level	**0.219** ***	**0.202** ***	**0.274** ***
Occupation status (working)	**0.467** ***	**0.383** ***	−0.078
Relevant to CE working experience	**1.064** ***	**0.654** ***	**−0.400** ***
Income satisfaction	**0.079** ***	**0.099** ***	**0.062** ***
Political ideology (right)	**0.157** ***	**0.097** ***	**−0.109** ***
Environmental concerns	**0.106** ***	**0.289** ***	**0.672** ***
Model Summary Table, R Square	0.183	0.180	0.122
Model Summary Table, Durbin Watson	1.833	1.921	1.978
ANOVA Table, Sig. value	Sig. = 0.000	Sig. = 0.000	Sig. = 0.000
Variance Inflation Factor	<1.6	<1.6	<1.6

*p < 0.10, **p < 0.05, ***p < 0.01

4 Conclusion

This study investigates citizen perceptions on CE and climate change mitigation and the socioeconomic factors that affect citizens' awareness through a quantitative survey conducted in nine European countries (Denmark, Germany, Italy, Poland, Portugal, Romania, Spain, and the United Kingdom). The analysis reveals that citizens' perceived knowledge of the CE is lower than their perceived knowledge of climate change mitigation. The most recognised CE practices among citizens are recycling, reuse, and repair, while the least recognised were refuse and rethink. Citizen awareness about the CE and climate change mitigation, on statistically significant level, depends on respondents' living area, age, education level, working status, income, relevant to CE working experience, political ideology and environmental concerns. On the other hand, citizen awareness of CE "R" practices, on statistically significant level, depends on age, education level, relevant to CE working experience, political ideology and environmental concerns.

This study is expected to advance understanding of citizens' perceptions and help develop targeted strategies and policy recommendations to increase circular economy awareness, leading to a sustainable built environment, in line with the EU's ambitious target to be climate-neutral by 2050.

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Exposing Assumptions in Smart Home Technologies: Insights from a Case Using Norm Critical Persona

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Abstract. This article investigates how smart home technologies embed power relations. Drawing on feminist STS, feminist posthumanism, and Bateson's transcontextuality, we conceptualise smart homes as socio-technical assemblages. The case exposes hidden assumptions and demonstrates how norm-critical perspectives can support more inclusive and ethically grounded smart home design.

Keywords: norm-critical · smart home · design · speculative · persona

1 Introduction

This paper is motivated by the disconnect between technical innovation in smart and regenerative building systems and wellbeing outcomes. We argue that without accounting for norm-critical analysis and socio-demographic differences of building users, smart home solutions risk reproducing and reinforcing white, male, middle-class and heteronormative cultures [1]. The vision of smart buildings has been pushed forward by technological progress that promises to optimise energy performance and reduce carbon dioxide emissions. We have seen more and more technology such as the Internet of Things (IoT), wireless sensor networks, and artificial intelligence (AI)-based decision-making systems being adopted [2]. Concurrently, the overall building sector is pivoting toward circularity paradigms that emphasize material reuse, life-cycle extension and regenerative resource loops. However, much like technical efficiency metrics, these circular models are often conceptualized through economic or techno-centric lenses, putting less emphasis on how everyday domestic practices influence practical implementation of circular systems. Moreover, a recent review of the literature shows that particularly "smart" building innovations are facing adoption and deployment challenges, such as interoperability issues, data security vulnerabilities and high integration costs [2].

In addition to the challenges above, there are also social and equality aspects related to smart technologies. For example, Bäcklund [3] asserts that smart building occupants are frequently positioned as passive recipients, and their opportunities for interaction are deliberately minimised. Hence, they are left out from important decisions about their everyday life and comfort. These dynamics also raise questions about what kinds of

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users smart building systems implicitly imagine and support. Design choices embedded in data infrastructures, automation logics, and interfaces can construct particular "ideal users" while marginalising others. Moreover, the digital infrastructures and the data underpinning smart buildings often reinforce the exclusion of certain groups. Decisions about what data to collect and analyse are closely related to broader contexts of governance and power [4]. Applied to smart buildings, D'Ignazio and Klein's framework suggests that sensor-driven systems governing energy use, comfort and safety are not merely technical solutions but socio-technical infrastructures whose omissions (e.g. the under-representation of certain tenants or atypical patterns of use in the datasets) may produce inequitable outcomes and significant blind spots in building governance.

To examine how such exclusions emerge and how they can be addressed, this paper draws on feminist posthumanism and feminist science and technology studies (STS). These perspectives conceptualize smart homes not as neutral technologies but as socio-technical assemblages through which norms, subjectivities, and relations of power are produced and reproduced. This paper presents a methodological analysis grounded in design research, centred on the case on the case Smart Killjoy. The case is not treated as empirical data in a conventional sense, but as a critical design artifact that enables analytical investigation of how norms and power relations are embedded in smart home technologies. The approach highlights how technical design choices embed assumptions about gender, agency and participation in smart and regenerative building environments.

1.1 Norms and Gender in Smart Homes

Despite being framed as transformative for both our everyday life and wider sustainability agendas, research around smart homes often leave established social norms largely intact. As a case in point, Hamarowski et. al. [5] have reviewed 92 cross-disciplinary publications about "smart homes" to assess to what extent gender has been addressed in this field. Their review shows that gender is seldom examined in a theoretically robust or intersectional way, with most research reducing it to a binary demographic category, thereby constraining critical insight. As a conclusion, Hamarowski et. al. [5] emphasise the need for more reflexive and inclusive frameworks in future scholarship, policy and design. When the development of domestic environments is driven predominantly by technological advancement and economic imperatives, there is a substantial risk that certain segments of the population will be marginalised and, in the most serious instances, adversely affected [6]. Ho and Vaara [7] argue that decentralising visions for alternative futures is one approach to expose the normative underpinnings of contemporary technological visions. Oliveira and Prado [8] critique of colonialist tendencies in speculative design further emphasises the importance of generating counter-imaginaries that resist universalist and exclusionary solutions. This framing supports our use of the Smart Killjoy persona as a method for articulating more situated, plural and politically attentive visions of smart home life.

Strengers [9] document how ostensibly "intelligent" systems are designed around a masculine "Resource Man"/idealized 1950s housewife archetype, with gendered expectations of care, control, and convenience embedded in devices and interfaces, dynamics that can marginalise users and narrow definitions of "success" to technical performance rather than lived wellbeing. Moreover, research over the past decade has shown that

the narratives surrounding smart homes are often misleading, highlighting risks such as the reinforcement of gender roles, increased digital exclusion, compromised privacy and the potential for increased domestic violence [10–12]. Politically attentive personas have demonstrated value in making values, ideologies and exclusions explicit in design—even when the goal is not market fit but public, situated critique [13, 14]. In addition, Scandinavian norm-critical design shows that discursive artefacts (e.g., the Androchair) can reconfigure conversations in organisations, rendering gendered infrastructures visible—an ethos mirrored by Smart Killjoy as a deliberately activist persona that contests smart-home techno-optimism [15].

2 Theoretical Framework

Feminist STS demonstrates how power and norms are embedded in and maintained through technical infrastructures, meaning that smart homes take part in shaping gendered and social relations. This becomes visible, for example, in the command logic structures in voice and home-automation systems, where interactions build their interaction on instruction and compliance. When smart systems adopt feminised voices, they reproduce historically female-coded tasks and service roles. Wagman and Parks' notion of the social machine extends this view by stressing that such systems function not merely as tools but as relational actors whose design shapes how agency, responsibility and authority are distributed within the home [16]. Smart technology thus generates not only functionality but also particular modes of relating between people and machines, and between households and infrastructures.

Drawing on Braidotti's feminist posthumanism, smart homes are not neutral technologies. They also shape who we are and how we live, because they are designed with certain ideas about "normal" users and behaviours [17]. Braidotti's posthumanist perspective helps uncover how smart homes work within broader assemblages of bodies, technologies and norms that mutually transform each other. This approach makes visible the ways smart systems not only support daily practices but actively influence subjectivity, agency and relational capacities within domestic life. To situate these dynamics, we draw on Nora Bateson's concept of transcontextuality [19], which highlights how relations emerge across multiple, simultaneous contexts. This perspective reveals how household practices, energy policy, economic models, and design norms interact in shaping the meanings and possibilities of smart home technologies. Bateson further highlights how the command logic of many smart homes appears frictionless because they detach decisions from the contexts in which they are embedded (i.e. household negotiations or gendered expectations). Bateson points instead to the need to attend to these relations across contexts, making visible how design choices, energy systems and everyday care practices intersect in smart home life [19].

Taken together, these perspectives approach smart homes as socio-technical arrangements where technologies, infrastructures and everyday practices shape relations of agency and responsibility. The concepts of the "social machine" and transcontextuality extend this view by situating smart homes within wider relations, across household dynamics, infrastructures, and economic and ecological contexts, making it possible to analyse how domestic automation both organises everyday life and reproduces patterns of power and exclusion.

3 Case Study: Norm-Critical Design as Intervention

This section examines emerging practices, such as more equitable operational models, and interrogates how norm-critical design can redistribute agency, reduce inequalities and support more inclusive smart homes. In particular, we examine how a design research case conceptualises smart homes as socio-technical assemblages where norms and power relations become materialised. Rather than treating power as an external structure reflected in technology, we analyse how the case presents power as produced through the interaction of design choices, data logics and everyday use. By examining the case "Smart Killjoy" (see section "Smart Killjoy: case description"), we have two analytical objectives:

1. Tracing how norms are materialized in infrastructures: i.e. analysing how technical choices carry with them and reproduce cultural and social assumptions.
2. Making visible how power is stabilised through socio-technical alignment: i.e. how people adapt to technology, and how technology shapes actions, priorities and responsibilities in the home.

The two analytical objectives functioned as methodological lenses that structured the interpretation of the Smart Killjoy case, rather than as general themes or outcomes. They guided both what to look for in the material and how to interpret what was found.

3.1 Case Description: Smart Killjoy

In this section, we examine a case "Smart Killjoy" within the Swedish research project "Smart Homes Through a Norm-Critical Lens" [20]. The Smart Killjoy case was selected as an instrumental and critical case. It originates from the research project "Smart Homes Through a Norm-Critical Lens", which explicitly aims to interrogate assumptions about gender, agency, and everyday life embedded in smart home systems. The project prototypes smart-home technologies, while examining power, gender and everyday practices. The research group develops design prototypes that reveal how norms become embedded in everyday household technologies, and has created "Smart Killjoy", a critical persona designed as a counter-narrative to tech-optimistic smart-home visions that functions as a tool for performing norm-critical design. "Personas" are used in feminist research as a critical lens to analyse the gendered "imagined users" embedded in smart-home industry narratives, showing how these simplified figures shape technology design while failing to reflect the messy realities of everyday household life [1].

The Smart Killjoy persona is originally inspired by Sara Ahmed's "Feminist Killjoy" [18] and is a methodological tool for uncovering power, norms, and sociotechnical imaginaries in smart home infrastructures. It is a persona that exposes power, norms and invisible inequality in the wake of digitalisation and acts as a counter-voice to the industry's cheerful visions. As a persona, the Smart Killjoy is questioning who benefits and who is harmed; and as a speculative design tool, it guides the creation of counter-images, illustrated by Ehrnberger et al. in [10] in the form of a dystopian smart-home advertisement, that challenge industry visions of technological utopia. The advertisements contrasts with typical industry marketing portraying seamless automation, sustainability, and happy nuclear families and exposes potential dystopian dimensions of smart

homes (i.e. surveillance, social inequality, and hidden ecological costs), e.g. by statements such as "Eco-smart living: Change nothing, look like you care". Thereby it is functioning as a discursive and speculative design artifact intended to provoke critical reflection on dominant smart-home narratives.

3.2 The Smart Killjoy Case Through the Lens of Our Analytical Objectives

Tracing How Norms Materialize in Infrastructures: Drawing on Nora Bateson's transcontextual perspective, Smart Killjoy can be used as a design method to reintroduce contexts often excluded by dominant smart home narratives. The approach stages conversations where multiple contexts remain visible (i.e. household relations, energy markets, climate impact) supporting decisions that are relational and ecologically informed rather than optimized for an isolated user. It can also highlight how seemingly small domestic commands depend on global infrastructures of resource extraction, manufacturing, data centres, and waste management. Making these hidden material and energy dependencies visible therefore becomes an ethical responsibility in the design of smart home systems [16, 17]. By situating power relations in the infrastructure itself, the Smart Killjoy case also unfolds (in line with both feminist materialism and feminist STS) that smart homes perform power rather than merely reflect it. Energy routines, automation, user interfaces and the distribution of everyday work, emerge as interconnected mechanisms that continuously make certain ways of living and acting legitimate and others less conceivable. In line with Wagman & Parks, this is also about unlearning: actively deprogramming normative assumptions about political neutrality, and a self-evident right to control via commands.

Making Visible How Power Is Stabilized Through Socio-Technical Alignment: Smart Killjoy has the potential to help design researchers unfold how technology, market narratives, and societal ideals interact to create stable power structures that privilege certain users. The norm-critical prototype of Killjoy functions as interventions that break these stabilizations by making the norms materially visible. In dialogue with Wagman & Parks, such interventions can be guided by two design challenges: non-anthropomorphic figuration (which avoids portraying the system as a feminised "assistant" and thereby de-naturalizes servant labor in the interface) and relations of mutuality, where the system does not simply obey commands but enables negotiation, declination, and feedback between household members, and between human, norm and machine.

Research on personas in Design research and HCI shows that they can be mobilised not only for empathy and communication but also for political and social consciousness, explicitly surfacing values, power and exclusions. By clarifying which assumptions are embedded in automation; and which subjects are made invisible; a different reading of smart home technology is created where alternative relationships between humans and technology can emerge. The Smart Killjoy persona reinforces this by acting as a politically disruptive figure who uncovers the materialization of power and opens up a broader spectrum of posthuman subjectivities. For example, the Smart Killjoy can expose hidden assumptions in automation by questioning design choices, such as challenging a smart thermostat that lowers heating during the day by highlighting how it assumes a 9–5 household routine and overlooks users such as people working from home or elderly residents.

3.3 Conclusions and Implications

Drawing on feminist STS, feminist posthumanism and Bateson's concept of transcontextuality, this article has argued that smart homes are socio-technical assemblages that embed norms, distribute agency and shape domestic relations. This has the power to reframe subjectivity as embodied, embedded and distributed, challenging universalist "ideal users" and instead emphasizing relational agency—a view that supports methods which situate domestic automation within broader socio-technical ecologies (e.g., energy infrastructures, data infrastructures, labor) [17]. In parallel, Bateson's transcontextuality and warm data argue that governance and design choices must be read across multiple overlapping contexts (household, grid, economy, care, ecology), suggesting that personas should retain and communicate context rather than strip it away. This perspective enables a critical reframing of subjectivity as relational and situated, supporting more inclusive design approaches; however, translating such theoretical insights into scalable and industry-accepted solutions remains challenging.

While methods such as the Smart Killjoy persona effectively expose hidden assumptions and broaden the understanding of users, they may face challenges in integration within standardised development processes focused on efficiency and market fit. Extending Strengers' "Resource Man", the Smart Killjoy persona operates as a disruptive figure that reveals how norms become embedded in automation, interfaces and data infrastructures, while questioning who benefits, who is excluded and what forms of labor remain invisible. This disruption provides a valuable tool for surfacing inequalities and encouraging reflection, yet it also risks being perceived as critical without offering immediately actionable solutions for practitioners.

The analysis presented in this paper points toward five concrete principles for designers, building operators, and policy actors working with smart home technologies.

1. Design for plural subjects, not ideal users. Designers should actively map who is made invisible by default design choices and use norm-critical personas as instruments for exposing and challenging those assumptions from the earliest stages of the design process.
2. Make context visible, not just data. Systems need to be designed to show contextual information such as care routines, household negotiation, energy dependencies, and ecological costs rather than optimizing for isolated efficiency metrics.
3. Replace command logic with relational interaction. Designers and building operators should move toward interaction models that enable negotiation and feedback between household members, between residents and building systems, and between users and data infrastructures.
4. Policy actors and building operators rarely have tools for evaluating the social assumptions embedded in smart building systems at the point of procurement. Public procurement frameworks for smart buildings should require evidence of norm-critical analysis. The Smart Killjoy methodology offers one practical instrument for this kind of structured critical review.
5. Treat maintenance and care as design material. Designers and operators should map who performs invisible domestic labour, make it visible in system design, and actively redistribute it rather than naturalising it as a user responsibility. Considering maintenance as a core design feature embeds the smart home within the socio-technical

frameworks of the circular economy. Architectural circularity cannot rely solely on automated, low-carbon technologies; it is contingent upon the equitable distribution of the socio-domestic labor (e.g. cleaning and troubleshooting) required to sustain those closed-loop systems over time.

While this shift enhances agency and inclusion, it introduces challenges regarding complexity, usability, and technical feasibility. Moving away from gendered or seamless interfaces may increase cognitive load of users or conflict with established interaction paradigms. Aligning personas with feminist STS, feminist posthumanism and transcontextual analysis, we see value in treating personas as relational subjects whose identities, agencies and vulnerabilities are co-produced with infrastructures, ecologies and devices. Future research paths may involve pairing persona work with Warm Data Labs or equivalent transcontextual practices so that personas carry context (e.g., care routines, tenancy regimes, energy markets, climatic conditions) and remain adaptive over time.

Re-centering on personas clarifies our overarching contribution: norm-critical personas (e.g., Smart Killjoy) are not simply empathy tools but methodological devices that—when informed by posthuman relationality and transcontextual warm data—can redistribute agency, surface infrastructural harms, and broaden domestic futures beyond optimization logics. This reframing helps ensure that the "imagined users" of smart homes are not singular, universal or disembodied but plural, situated and relational, with design obligations that extend across households, infrastructures and ecologies

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Beyond Consumption: The Active Citizen and the Ethics of Market Transformation in a Circular Built Environment

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Abstract. The transition toward sustainable and circular economic systems requires a fundamental rethinking of how markets operate and how citizens interact with the built environment. The main objective of this study is to examine the role of the active citizen in driving ethical market transformation and supporting the development of a circular and sustainable built environment. The paper argues that moving beyond the traditional concept of the "consumer" toward that of the "active citizen" provides a solid foundation for ethical, transparent, and socially responsible market practices. The analysis explores how civic engagement, collective responsibility, and participation in decision-making processes influence sustainable development outcomes. The study highlights the multidimensional role of the active citizen as a user of spaces, a co-creator of value, and a participant in community initiatives that strengthen social cohesion and ecological resilience. Through informed choices, support for sustainable brands, and involvement in local urban regeneration projects, citizens become essential drivers of change, while ethical marketing practices—centered on transparency, truthful communication, and long-term social impact—facilitate this transition. The empirical methodology is based on a structured questionnaire applied among citizens, aiming to assess their perceptions, behaviors, and attitudes toward sustainability, ethical marketing, and the circular economy, as well as the determinants of civic engagement. The findings provide empirical evidence on the factors that encourage responsible behavior and active participation, supporting the proposed conceptual framework of market transformation toward circularity. The analytical contribution of the study lies in integrating ethical marketing principles with civic engagement theory and circular economy concepts, while its practical contribution consists in offering actionable guidelines for policymakers, urban planners, and businesses seeking to design sustainable marketing strategies and participatory initiatives in the built environment. The article is elaborated within the context of the project 'Strengthening socio-economic and legal mechanisms for ensuring the well-being and security of citizens' (CONSEJ 01.05.02).

Keywords: Active citizen · ethical marketing · circular economy · sustainable built environment · market transformation

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1 Introduction

In the face of global challenges such as climate change, environmental degradation, and increasing pressure on natural resources, the traditional linear economic model—based on the "extract–produce–consume–dispose" paradigm—is increasingly being questioned due to its inherent structural limitations and its adverse effects on both economic and ecological sustainability. This model of development has contributed to a rise in waste production, heightened consumption of finite resources, and growing tensions between economic growth and environmental preservation. In this context, the concept of a circular economy has emerged as a strategic framework for transforming contemporary economic systems.

The circular economy represents a regenerative economic system in which products and materials are kept in circulation for as long as possible through processes such as reuse, repair, refurbishment, and recycling, thereby reducing waste generation and mitigating the impact on natural resources. According to the Ellen MacArthur Foundation, the circular economy aims to prevent waste and pollution by designing products for longevity, maintaining materials in economic use, and restoring natural systems [1].

In the scholarly literature, the transition to a circular economy is associated not only with technological and industrial innovations but also with significant changes in consumer behavior and the ways in which consumers contribute to market functioning. Consequently, the modern consumer is increasingly viewed not merely as a passive economic participant focused on satisfying personal desires, but as an active citizen capable of influencing corporate practices and market directions through responsible consumption choices and support for sustainable initiatives.

Consumer ethics is becoming increasingly important, as consumer actions can shape organizational strategies, promoting the development of business models centered on resource efficiency and product longevity. Within this context, the circular economy is perceived as a systemic approach aimed at decoupling economic growth from excessive resource use and achieving a balance between economic progress, social well-being, and environmental conservation [2].

The study examines how citizens adopt responsible and sustainable behaviors, as well as the role of public institutions and brands in promoting ethical values and the principles of the circular economy. The research is based on a review of the relevant literature and on data collected through a consumer survey investigating respondents' perceptions, attitudes, and behaviors regarding environmentally friendly and sustainable consumption practices.

A significant area of research focuses on the factors influencing consumer behavior within the circular economy. Recent studies indicate that the adoption of circular practices—such as recycling, reusing goods, and participating in collaborative consumption—is driven by factors including environmental awareness, social norms, and the availability of recycling and reuse infrastructure. The findings suggest that behavioral change requires a combination of educational, economic, and institutional factors that support the integration of sustainability principles into everyday consumption choices [3].

Nevertheless, group initiatives—such as reuse communities, sharing platforms, or local recycling groups—can have a significant impact on the adoption of sustainable

behaviors. These social structures facilitate the circulation of information, promote ecological social norms, and strengthen the social capital essential for amplifying circular economy practices [4].

At the same time, the literature emphasizes the role of collaboration in value creation between consumers and firms within circular models. In these models, consumers are not merely product users but become active participants in processes such as reuse, repair, or returning products into the circular economy. This approach highlights the transition from a traditional consumption model to a collaborative one, in which economic value is generated through the cooperation of various stakeholders within the economic system [5].

Thus, current research indicates that the success of the circular economy depends not only on technological innovations or institutional frameworks but also on changes in consumer behaviors and principles. In this context, evaluating the role of the active citizen becomes crucial for understanding how consumption habits can influence market reconfiguration and reinforce an economic model oriented toward sustainability.

In recent literature, the circular economy is described as a systemic shift in the way resources are utilized and valorized within the economy. Geissdoerfer et al. emphasize that this model represents a new paradigm of sustainability, focused on keeping resources in economic circulation for as long as possible while reducing environmental impact. The transition to a circular economy involves not only technological innovations but also transformations in consumer behavior and market practices [6].

Simultaneously, the adoption of sustainable behaviors can be explained through well-established consumer behavior models. According to the Theory of Planned Behavior, personal attitudes and perceived social norms influence individuals' intentions and actions. Within the circular economy, this perspective suggests that the level of sustainability awareness and perceptions of organizational and corporate responsibility can facilitate the integration of responsible consumption practices [7].

Building on these theoretical perspectives, the present study examines how the level of sustainability awareness, perceptions of ethical marketing, and the role of institutions influence responsible consumption behaviors and civic engagement.

The objective of this research is to analyze the role of active citizens in supporting the ethical transformation of the market and the development of a circular and sustainable built environment. Based on the premise that the level of environmental awareness, perceptions of ethical marketing, and the involvement of institutional stakeholders may influence consumer behavior, the following hypotheses are proposed:

H1: A higher level of awareness of sustainability principles is positively associated with the adoption of responsible consumption practices.
H2: A positive perception of ethical marketing influences consumers' attitudes toward responsible consumption behaviors.
H3: The perceived involvement of public institutions and companies contributes to increasing citizens' willingness to participate in sustainability and circular economy initiatives.

2 Materials and Methods

For the development of the theoretical framework, a narrative review of the literature on the circular economy, ethical marketing, and sustainable consumption behavior was conducted. Relevant scientific articles, reports, and institutional documents were analyzed and used to establish the conceptual framework and formulate the research hypotheses.

The empirical research was carried out using a survey-based approach, employing a structured questionnaire developed through Google Forms. The research instrument was designed to assess citizens' perceptions, attitudes, and behaviors regarding sustainability, the circular economy, and the ethical dimension of consumption decisions. Data collection was conducted online, with the questionnaire distributed via communication platforms such as Telegram, WhatsApp, and Messenger, as well as through email. Participation in the study was voluntary and anonymous. The study was conducted in the Republic of Moldova between January and March 2026. The survey link was distributed to approximately 680 individuals. A total of 504 questionnaires were collected and validated, corresponding to a response rate of 74.1%. The sample was non-probabilistic and based on respondents' willingness to participate in the research. The collected data were processed using descriptive statistical analysis methods. Frequencies and percentage distributions were calculated for each variable examined in the study. Building on these theoretical perspectives, the present study examines how the level of sustainability awareness, perceptions of ethical marketing, and the role of institutions influence responsible consumption behaviors and civic engagement.

3 Results and Discussions

The socio-demographic structure of the sample is presented in Table 1. As shown, the distribution of respondents is relatively balanced in terms of gender, with a slight predominance of female participants. The most represented age group is 26–35 years**,** and the majority of respondents hold a higher education degree. Regarding the area of residence, the distribution is relatively balanced between urban and rural areas.

Regarding the question on *the level of familiarity with sustainability and circular economy concepts*, the results indicate a high degree of awareness among respondents. The majority of participants consider themselves well-informed (50.2%), while 6.2% report being very well-informed, reflecting a consolidated presence of these concepts within social and educational contexts. At the same time, 39.9% of respondents exhibit a moderate level of familiarity, suggesting potential for further knowledge development. The low percentages of those who are slightly familiar (3%) or not familiar at all (0.8%) confirm the widespread dissemination of sustainability topics in contemporary public discourse, a trend also highlighted in the literature on increasing awareness of the circular economy at the European level [8].

Concerning the question on *the importance of sustainable development in the built environment for quality of life*, the results show a high level of appreciation among respondents, with most assigning high scores: 53.8% selected level 4, and 28.4% the maximum level (5). The very low proportion of low ratings demonstrates a clear consensus regarding the positive role of sustainable buildings, housing, and public spaces in improving quality of life.

Table 1. Demographic characteristics of respondents.

Variable	Category	Percentage
Gender	Male	44.6
	Female	55.4
Age	18–25 years	14.9
	26–35 years	26.4
	36–45 years	20.8
	46–55 years	22.8
	Over 55 years	15.1
Education Level	gymnasium	0.6
	High school	9.7
	Tehnical	19.8
	Higher Education	50.4
	Postgraduate	19.4
Place of Residence	Urban	50.0
	Rural	50.0

Source: Author's elaboration.

The responses indicate a predominantly positive perception of citizens' *capacity to influence urban regeneration and sustainability processes*. The majority of respondents believe that civic engagement has a significant impact, with 256 participants rating the influence as high and 99 as very high. A smaller number of participants (135 respondents) perceive the influence at a moderate level, while skeptical opinions are nearly absent (13 responses – low, with no responses for "none"). This distribution reflects a clear recognition of the active role of citizens in sustainable urban development and suggests an orientation toward participation and collective responsibility in shaping the urban environment.

Regarding the extent to *which respondents consider ethical and environmental criteria when purchasing products or services*, the results show that these aspects are frequently taken into account in consumption decisions. Half of the participants (50.2%) report considering such criteria often, and 34.1% indicate they do so sometimes, reflecting a general tendency toward more responsible consumption behavior. Only 5.2% rarely take these aspects into account, and 0.4% never do, while 10.1% state that they always incorporate them into their decisions, highlighting the presence of a core group of consumers consistently applying ethical and environmental principles.

Regarding the statement on *the preference for brands that promote sustainability, transparency, and social responsibility*, the responses indicate a clearly positive orientation among participants. The majority of respondents expressed agreement (60.7%) or strong agreement (17.9%), reflecting a high openness toward brands perceived as responsible. The proportion of neutral respondents (18.7%) suggests the presence of a segment that remains undecided or less engaged, while disagreement is very low (2%)

and almost nonexistent in the form of strong disagreement (0.8%). The distribution of results highlights a favorable trend toward valuing social responsibility and sustainability in consumer–brand relationships.

In response to the question *"Which sustainable practices do you currently adopt?"*, the most frequently reported practices are energy saving (74.8%) and consumption reduction (69.8%), followed by reuse and repair (55.2%). Recycling is adopted by 35.5% of participants, while the use of public or alternative transportation is reported by only 27%, suggesting that respondents prefer individual measures that are easy to implement at home, whereas practices requiring behavioral change or infrastructure are less widespread. These findings indicate the need for policies that combine environmental education with improvements in infrastructure for alternative transportation and recycling.

The results of the question *"Have you ever participated in community initiatives or urban regeneration projects?"* indicate a relatively high level of civic engagement among respondents. Specifically, 63.7% of participants reported having taken part in such activities, while 36.3% had no prior experience in this regard. These findings suggest a significant openness to community participation, reflecting a favorable trend in the development of civic behaviors associated with sustainability and social responsibility.

Regarding the statement *"I believe citizen involvement is essential for the development of a sustainable built environment,"* the majority of respondents recognize the importance of civic participation: 57.1% agree, and 16.5% strongly agree. Only a small proportion expressed disagreement (0.8% disagree, 0.4% strongly disagree), while 25.2% remained neutral. These results indicate that citizen engagement is perceived as a key factor in sustainable urban development, although a portion of the population has yet to form a clear opinion.

In response to the question *"To what extent are you willing to actively participate in community sustainability projects?",* most respondents expressed a high level of willingness: 51.4% indicated "Much" and 14.3% "Very much," while 31.5% reported a moderate level. Only a very small percentage showed reluctance, with 2.4% responding "Little" and 0.4% "Not at all." These findings demonstrate significant interest in active participation in sustainable initiatives, suggesting a real potential for mobilizing communities in environmental and sustainable development projects.

Regarding the statement *"Do you believe that ethical marketing can positively influence responsible consumption behavior?"*, the results show that the majority of respondents recognize the positive effect of this practice: 278 participants rated the influence as "Much," and 75 as "Very much." A significant segment (138) assessed the impact as "Moderate," while only 12 respondents considered the influence to be low ("Little"), and none indicated "Not at all." These findings indicate a widespread confidence in the capacity of ethical marketing to stimulate responsible consumption behaviors.

The results concerning perceptions of *the responsibility of public institutions and companies in promoting the circular economy show* that most respondents consider it significant: 54.6% rated it as "High," and 20.6% as "Very high." Approximately 23.4% perceived it as "Moderate," while only 1.2% considered it "Low," and no respondents selected "Very low." These data highlight a clear awareness of the essential role of public and private actors in supporting sustainable practices and the circular economy.

The responses provided by participants to the question *"In your opinion, what changes are necessary in the Republic of Moldova to encourage more responsible and sustainable behavior regarding the built environment?"* highlight several key directions:

- *Education and Awareness:* Informing the population about the consequences of uncontrolled urban development and the importance of recycling.
- *Citizen Engagement:* Active participation in community projects and cleanliness initiatives.
- *Role of the State and Legislation:* Implementation of stricter regulations, establishment of sanctions for pollution, mismanagement of waste, and unauthorized construction.
- *Infrastructure:* Expanded public transportation, bicycle lanes, green housing, and facilities supporting sustainable practices.
- *Shared Responsibility:* Citizens, companies, and institutions engaged in promoting a sustainable built environment.

In response to the question *"What role should public institutions and commercial brands play in promoting ethical values and the circular economy?"*, respondents indicated that these actors should adopt an active role, combining clear policies and regulations, sustainable products and practices, awareness campaigns, and citizen engagement, acting both as exemplars and as incentives for responsible consumption.

The overall analysis of the questionnaire highlights a clear interest and openness among respondents toward sustainability and civic engagement. The results suggest that citizens are aware of the impact of their actions on the environment and are willing to adopt responsible behaviors. However, transforming this willingness into concrete practices requires effective mechanisms for support, motivation, and coordination among the community, institutions, and the private sector. This combination of individual responsibility and structural support can constitute a decisive factor in developing a sustainable urban environment and a functional circular economy.

4 Conclusion

The research findings confirm the essential role of the active citizen in supporting the transition toward a circular economy and a market model grounded in ethical responsibility. The analysis of the scholarly literature, complemented by data collected through the consumer survey, demonstrates that the level of awareness of sustainability principles significantly influences the adoption of responsible consumption behaviors, supporting H1. Informed consumers exhibit greater openness toward sustainable choices and more frequently integrate ecological values into their daily purchasing decisions.

Furthermore, the results indicate that positive perceptions of ethical marketing contribute to the formation of favorable attitudes toward responsible consumption, confirming H2. Transparent communication oriented toward social and environmental values strengthens trust in brands and encourages consumer engagement in sustainable consumption practices.

At the same time, the research validates H3, highlighting that the perceived engagement and responsibility of public institutions and companies increase citizens' willingness to participate in sustainability and circular economy initiatives. Overall, the

transformation of the market toward sustainable economic models depends on collaboration among citizens, organizations, and institutions, with the active citizen emerging as a central actor in redefining the relationship between the market, society, and the environment.

Simultaneously, the study presents certain limitations that should be acknowledged. The research relies on self-reported data collected through an online questionnaire, which may introduce some response biases. Additionally, the sample is not strictly probabilistic, which may limit the generalizability of the results to the entire population.

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From Green Education to Sustainable Development: Transformations for the Circular Economy

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Abstract. The transition to a circular economy has become one of the global priorities of sustainable development. Education is often considered a key foundation for sustainable development, contributing to human capital formation, innovation, and social well-being. At the same time, the development of the circular economy depends on a range of interconnected factors, including institutional quality, technological innovation, the overall level of socio-economic development, and behavioral and cultural conditions. This study aims to assess the relationships between educational, institutional, and innovation-related factors and the level of circular economy development in European countries. The research is based on a multi-stage quantitative and multivariate statistical analysis. A composite Circularity Index was constructed using Principal Component Analysis. The institutional environment was evaluated through factor analysis based on the Worldwide Governance Indicators (WGI), while correlation analysis was applied to examine relationships between the circular economy index and selected explanatory variables. The results indicate that circular economy development is most strongly associated with the Human Development Index, Environmental Performance Index, and the Eco-Innovation Index. In contrast, the Sustainable Development Goals 4.7.1 indicator, measuring the integration of education for sustainable development in education systems, shows only a weak relationship with the Circularity Index. The study contributes to the understanding of the systemic drivers of circular economy development and highlights the indirect role of education through human capital and innovation capacity.

Keywords: Circular economy · Sustainable development · Eco-innovation · Institutional quality · Human development · SDG 4

1 Introduction

Global best practices indicate that the successful implementation of a circular economy requires a systemic approach in which public strategies and educational systems operate in a complementary manner. Education for Sustainable Development (ESD) plays an important role in addressing global challenges and contributes to the achievement of the Sustainable Development Goals (SDGs). However, circular economy development

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depends on a number of interconnected factors, including human capital, institutional quality, technological innovation, and the development of the education system. In this context, education is often viewed as a long-term enabling factor that contributes to the formation of human capital and green skills, while its impact on circular economy development frequently occurs through indirect mechanisms.

Increasing attention is being paid to educational approaches that promote sustainable thinking, environmental awareness, and behavioral change [1, 2]. However, recent studies show that the integration of SDG-related topics into educational curricula often remains fragmented [3]. At the same time, sustainability-oriented educational projects may support circular economy practices such as resource efficiency and waste reduction. Since the built environment is one of the largest consumers of materials and generators of waste in Europe, the transition toward circular economy models increasingly depends on institutional capacity, eco-innovation, and sustainability-oriented education. Therefore, understanding the systemic drivers of circularity may also contribute to more sustainable construction and resource-efficient urban development policies.

In this context, it is important to understand the relationships between education, institutional development, and eco-innovation. This study aims to assess how human development, institutional quality, and eco-innovation are associated with the level of circular economy development, as well as to examine the potential indirect role of integrating sustainable development into education systems.

To achieve this objective, the following research tasks were formulated:

1. To analyze international circular economy indicators and construct a composite Circular Economy Index (Circularity Index).
2. To assess the institutional environment using factor analysis based on the Worldwide Governance Indicators (WGI).
3. To examine relationships between the Circularity Index and selected explanatory variables.
4. To evaluate the relationship between the integration of sustainable development in education systems (SDG 4.7.1) and the level of circular economy development.
5. To identify key drivers of circular economy development.

Within the framework of the study, the following hypotheses were formulated:

H1: Circular economy development is positively associated with the level of human development.
H2: Higher levels of eco-innovation are associated with higher levels of circular economy development.
H3: Countries with higher institutional quality tend to demonstrate higher levels of circular economy development.
H4: The integration of sustainable development into education systems is positively associated with circular economy development.
H5: Higher public expenditure on education may be associated with circular economy development through human capital formation and innovation capacity.

2 Literature Review

In the transition toward a circular economy, the education system can play an important role in fostering a more sustainable and inclusive society. Recent studies emphasize that this requires educational institutions to provide accessible learning tools [4], updated curricular content, and pedagogical approaches that promote critical and systemic thinking [5]. In this context, policymakers and educational administrators play a key role by integrating knowledge related to the Sustainable Development Goals (SDGs) and the principles of the circular economy into educational strategies.

At the same time, researchers frequently highlight the gap between individuals' environmental knowledge and their actual behavior [6]. Therefore, an important task of education systems is not only to transmit knowledge but also to develop the skills and values necessary for applying circular economy principles in everyday life and professional activities.

Several studies also note that the influence of education on sustainable economic models often occurs through indirect and long-term mechanisms. Education contributes to human capital formation, innovation, and the development of green skills necessary for circular economy transitions [7, 8]. Beyond educational factors, the literature also highlights the importance of the institutional environment. Within the framework of institutional economics, effective governance systems, regulatory stability, and institutional trust are regarded as key conditions for economic and technological transformations [9]. Countries with higher institutional quality are generally more capable of implementing environmental policies and supporting green innovation.

In addition, eco-innovation is widely recognized as a key driver of circular economy development. Technological innovation contributes to more efficient resource use, the transformation of production processes, and waste reduction [10]. Higher levels of innovation capacity enable economies to transition more rapidly toward sustainable production and consumption models.

Overall, the literature suggests that circular economy development is shaped by a combination of educational, institutional, and innovation-related factors. However, relatively few studies have examined these factors jointly in a comparative cross-country framework. This study addresses this gap by analyzing the relationships between education, institutional quality, eco-innovation, and circular economy development across European countries.

3 Data

The study uses comparative data for European Union countries, reflecting circular economy development, institutional environment, eco-innovation performance, and selected indicators of sustainable development and education. All variables were standardized prior to PCA and factor analysis to ensure comparability between indicators measured on different scales. After removing observations with missing values, the final sample includes 27 countries. The dataset represents the most recent available cross-sectional data for the period 2022–2024, depending on the specific indicator. Data were obtained from Eurostat, World Bank WGI, UNDP, and the UN SDG database.

To construct the Circular Economy Index, four indicators from the Eurostat database were used: circular material use rate, recycling rate of municipal waste, recycling rate of packaging waste, and private investment and gross value added in circular economy sectors.

Additional variables reflecting socio-economic development and potential drivers of circular economy development were included in the analysis: Human Development Index (HDI), Environmental Performance Index (EPI), Eco-Innovation Index (EcoInn Index), education expenditure as a percentage of GDP (EducExp), GDP per capita (GDP Cap), and the SDG 4.7.1 indicator measuring the integration of education for sustainable development into education systems.

Indicators of institutional development were obtained from the Worldwide Governance Indicators (WGI) database of the World Bank, which includes six aggregated governance indicators: Control of Corruption, Government Effectiveness, Political Stability, Rule of Law, Regulatory Quality, and Voice and Accountability.

All variables are used to examine the relationships between the level of circular economy development and institutional, innovation, and education-related factors.

4 Methodology

To analyze the relationships between the variables under study, a set of multivariate statistical methods was applied.

Figure 1 presents the conceptual framework linking education-related factors, human capital, institutional quality, and eco-innovation to circular economy development.

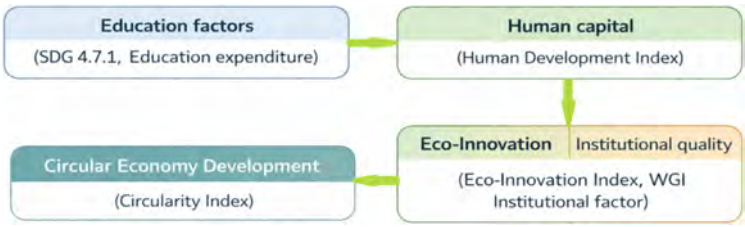


Fig. 1. Conceptual framework linking education, innovation, institutions, and circular economy development.

4.1 Construction of the Circular Economy Index

At the first stage of the study, a composite Circular Economy Index was constructed. For this purpose, the Principal Component Analysis (PCA) method was applied. Four circular economy indicators were included in the analysis. According to the Kaiser criterion, only one principal component was extracted, explaining approximately 65% of the total variance of the original variables.

All four indicators have high and similar factor loadings (in the range of 0.79–0.84), indicating a strong relationship between them and allowing the extracted component to

be interpreted as an integrated measure of the level of circular economy development in a country (Circularity Index). The similarity of factor loadings indicates the internal consistency of the constructed index.

Thus, different indicators reflecting waste recycling, the use of secondary materials, and investment in circular economy sectors effectively measure a single latent phenomenon - the overall level of circularity in the economy.

4.2 Factor Analysis of Institutional Indicators

To assess the institutional environment, factor analysis was conducted based on six indicators from the Worldwide Governance Indicators (WGI) dataset. The analysis employed the Principal Axis Factoring (PAF) method with Varimax rotation, with two factors extracted.

The quality of the factor model is confirmed by strong statistical indicators:

- Kaiser-Meyer-Olkin (KMO) = 0.897, indicating high suitability of the data for factor analysis,
- Bartlett's Test of Sphericity is statistically significant ($p < 0.001$),
- the total explained variance of the two factors is 86.8%,
- factor loadings below 0.40 were not interpreted.

The results of the factor analysis allowed the identification of two latent factors.

Factor 1 – Institutional Quality/Governance Capacity. This factor shows the highest loadings for the following variables: Government Effectiveness, Rule of Law, Regulatory Quality, and Control of Corruption.

It explains approximately 52% of the total variance and reflects the effectiveness of public administration, the quality of regulation, and the capacity of institutions to implement economic and environmental policies.

Factor 2 – Democratic Factor/Political Freedoms. The second factor is characterized by high loadings for the variables: Voice and Accountability and Political Stability.

It explains approximately 34% of the variance and reflects the level of political freedoms, government accountability, and democratic institutions.

Given the objectives and research tasks of this study, the subsequent analysis uses Factor 1 – Institutional Quality / Governance Capacity as the institutional quality factor.

4.3 Correlation Analysis

At the final stage of the study, correlation analysis was conducted between the composite Circularity Index and the selected explanatory variables. Table 1 reports the correlation coefficients between the Circularity Index and the selected explanatory variables.

The analysis is exploratory in nature and does not aim to establish causal relationships between variables. The results of the analysis show that the strongest relationships with the level of circular economy development are observed for the following indicators:

- Human Development Index (HDI) ($r \approx 0.53$)

Table 1. Correlation matrix between the Circularity Index and selected socio-economic, institutional, and innovation indicators for EU countries.

Variable	Circularity	EcoInn Index	Educ Exp	EPI	Factor1	SDG 4.7.1	HDI	GDP Cap
Circularity	1.00	0.49	0.37	0.52	0.37	0.10	0.53	0.23
EcoInn Index	0.49	1.00	0.32	0.59	0.79	0.07	0.75	0.59
Educ Exp	0.37	0.32	1.00	0.38	0.42	−0.04	0.31	−0.10
EPI	0.52	0.59	0.38	1.00	0.55	−0.16	0.61	0.42
Factor1	0.37	0.79	0.42	0.55	1.00	0.06	0.81	0.72
SDG 4.7.1	0.10	0.07	−0.04	−0.16	0.06	1.00	0.06	−0.06
HDI	0.53	0.75	0.31	0.61	0.81	0.06	1.00	0.78
GDP Cap	0.23	0.59	−0.10	0.42	0.72	−0.06	0.78	1.00

- Environmental Performance Index (EPI) ($r \approx 0.52$)
- Eco-Innovation Index ($r \approx 0.49$)

The findings also indicate that circular economy development is primarily associated with the level of human capital, the effectiveness of environmental governance, and the development of eco-innovation.

At the same time, the relationship between circular economy development and public expenditure on education as well as the institutional quality factor is of moderate strength:

- Education expenditure (% of GDP) – $r = 0.369$
- Institutional factor – $r = 0.367$

Meanwhile, the SDG 4.7.1 indicator, which reflects the integration of education for sustainable development into education systems, demonstrates an almost negligible correlation with the Circularity Index ($r \approx 0.10$).

4.4 Results

The hypotheses were tested using correlation analysis between the Circularity Index and the selected explanatory variables.

The results show that human development has the strongest association with circular economy development. The Human Development Index (HDI) demonstrates a relatively strong positive correlation with the Circularity Index ($r \approx 0.53$), supporting H1 and suggesting that countries with higher levels of human capital tend to achieve higher levels of circular economy development.

A similarly strong relationship is observed for eco-innovation. The Eco-Innovation Index shows a positive correlation with the Circularity Index ($r \approx 0.49$), providing support for H2 and confirming the important role of technological innovation in promoting resource efficiency and waste reduction.

Institutional factors also demonstrate a positive relationship with circular economy development. The Institutional Quality factor derived from the WGI indicators shows a moderate correlation with the Circularity Index ($r \approx 0.37$), providing partial support for H3.

In contrast, the SDG 4.7.1 indicator, measuring the integration of education for sustainable development into education systems, shows an almost negligible correlation with the Circularity Index ($r = 0.097$). Therefore, H4 is not supported, suggesting that the formal inclusion of sustainability topics in education policies does not necessarily translate into immediate circular economy outcomes.

Finally, education expenditure (% of GDP) shows a moderate-to-weak positive correlation with the Circularity Index ($r \approx 0.37$), providing partial support for H5 and indicating that education may influence circular economy development indirectly through human capital formation and innovation capacity.

Overall, the results indicate that circular economy performance is primarily associated with human development, environmental performance, eco-innovation, and institutional capacity, while the role of education appears indirect and long-term.

4.5 Discussion and Conclusion

The results of the study indicate that the development of the circular economy is more strongly associated with the overall level of socio-economic development than with the formal integration of sustainability topics into education systems. In particular, the relatively strong correlations between the Human Development Index (HDI) and the Environmental Performance Index (EPI) with the Circularity Index suggest that countries with higher levels of human capital and more effective environmental governance tend to demonstrate higher levels of circular economy development.

At the same time, the relatively high correlation with the Eco-Innovation Index highlights the important role of technological innovation as a key mechanism supporting the transition toward circular economy models. These findings suggest that the implementation of circular economy principles largely depends on innovation capacity, institutional effectiveness, and the broader socio-economic development of countries. Therefore, the results should be interpreted as associative rather than causal relationships. Similar relationships between innovation capacity and circular economy performance have also been identified in previous cross-country studies on sustainable economic transitions [10].

In contrast, the SDG 4.7.1 indicator, which reflects the integration of education for sustainable development into education systems, shows only a very weak relationship with the Circularity Index. This may be explained by several factors: the indicator is largely based on self-reported assessments of educational policies, it measures the existence of policy frameworks rather than actual educational outcomes, and it exhibits limited variation among developed countries. These findings are consistent with previous studies suggesting that educational reforms often require long-term institutional and behavioral transformation before measurable sustainability outcomes emerge.

Therefore, the findings suggest that the formal integration of sustainability topics into educational policies alone is not sufficient to drive circular economy development. Instead, education should be viewed as a long-term and indirect factor that contributes to the formation of human capital and innovation capacity. Over time, these elements may

create favorable conditions for the transition toward more sustainable economic models, where circular economy principles are increasingly applied through resource-efficient construction, waste reduction, and sustainable urban development strategies.

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Digitising Waste: Teaching Circular Construction Through Computational Workflows and Digital Fabrication

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Abstract. The transition toward a circular built environment requires not only technical innovation but a fundamental shift in engineering pedagogy. While theoretical models of circular economy are well-established, the practical application of reusing waste materials in structural design remains a complex challenge due to material variability and non-standard geometries. This paper presents the pedagogical framework and outcomes of a graduate-level course at Politecnico di Milano, designed to bridge the gap between theoretical circularity and digital fabrication. The methodology follows a "waste-to-resource" workflow, guiding building engineering students through three distinct phases: Urban Mining and Digitization, Computational Design, and Advanced Fabrication. The cohort was tasked with sourcing waste materials from the urban context, which were then catalogued and digitized. Leveraging a suite of computational design tools within the Grasshopper environment - including evolutionary solvers for optimization, nesting algorithms for material efficiency, and specific plugins for timber joinery - students developed parametric models capable of adapting to the irregularities of reclaimed materials. The course culminated in the fabrication of five large-scale architectural structures, utilising advanced manufacturing techniques including milling and 3D printing, specifically focusing on creating bespoke interfaces and connections that facilitate dry assembly and future disassembly. This paper discusses the successes and challenges of this pedagogical model, analysing how digital tools serve as essential enabler for scaling circular practices. By treating waste as a variable input for algorithmic design, the course demonstrates that digital fluency is a prerequisite for the next generation of engineers to effectively operationalize circular economy in construction.

Keywords: Circular Pedagogy · Urban Mining · Computational Design · Digital Fabrication · Design for Disassembly

1 Introduction

The construction sector is a primary consumer of raw materials and a major generator of waste, operating largely within a linear "take-make-dispose" model [1]. Transitioning to a Circular Economy (CE) requires moving towards reduction, reuse, and recycling of

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materials. To implement those, a paradigm shift is necessary, where existing building stock and demolition waste are viewed as material banks [2]. However, a significant gap exists in current engineering education: while students are taught the theory of circularity, they often lack the practical skills to handle the unpredictability of secondary resources. Unlike standard construction materials with certified properties and dimensions, waste is irregular, variable, and often contaminated.

This paper addresses the "Linear vs. Circular" gap by proposing a pedagogical framework that treats waste not as a problem, but as a "data-rich" resource. We argue that computational workflows are the key to unlocking the reuse potential of these materials. By digitizing waste - creating a "Digital Twin" of irregular scraps - designers can use parametric tools to adapt their structures to the material, rather than forcing the material to fit a standardized design. In this work we show that the design, becomes an iterative process, in which materials constraints inform the design development process, as well as the re-manufacturing processes inform the design in order to reuse existing materials. To demonstrate this thesis, the outcomes of a graduate course at Politecnico di Milano is presented, where students moved from theoretical "Urban Mining" to the physical fabrication of full-scale reversible structures. The course aimed to demonstrates the circularity of design to remanufacturing processes and to validate that digital fluency allows for the structural reuse of "junk," turning unpredictability into a design driver through computational logic.

2 Methods

The course was structured around a rigorous "Waste-to-Resource" workflow, divided into three interconnected phases, comprising urban mining and digital cataloguing, computational design based on stock-constrains, and hybrid re-manufacturing. This structure forced students to abandon traditional linear design processes (Design → Material selection) in favour of a circular approach (Resource Mapping → Design adaptation).

2.1 Phase 1: Urban Mining and Digitization

The first phase challenged students to identify, collect, and catalogue waste materials from the local urban context. This process went beyond simple scavenging. Students identified waste material coming from deconstruction of furniture, construction components, and other waste streams (Fig. 1). They used photography and physical measurement to capture the geometry of found objects (e.g., discarded timber in various forms and composition, pallets, polycarbonate panels, and plastic based components).

A comprehensive *Material Catalogue* was structured to develop a rigorous ID-based list that tracked the dimensions, material quality, and probable origin of every piece of collected material and component. As far as feasible, this was expanded into a "Digital Material Passport" concept, ensuring that the history and properties of the waste were embedded in the digital model from the start, effectively creating a simplified "Digital Twin" of the physical stock, that was shared among the students, to allow them to reserve quantities of the available materials for planning their design and then re-manufacturing for prototyping.



Fig. 1. Material stock

2.2 Phase 2: Computational Design

With the physical waste digitized into a database of 3D assets, students moved to the computational environment. The primary challenge was to design structures that could adapt to the fixed, irregular constraints of the reclaimed materials.

Students were introduced to a set of algorithms that could be employed to: design based on stock-constrained members, such as *Phoenix* [3]; model structures based on adaptive algorithms, such as *Kangaroo 2* [4], which is based on physics-based form-finding, and simulates forces, constraints, and material behaviour in real time, so that the structure adapts automatically to loads, tension, compression, or minimal surface, or *Galapagos* [5], based on evolutionary optimization, that allow changing design variables iteratively to meet goals like minimizing material, stress, or waste. As well as algorithms that can guide in the reduction of waste, from a given set of components, such as *Open Nest* [6], which can be used for 2D nesting optimization, to automatically arranges shapes inside a given area to minimize material waste, and can be particularly useful in manufacturing processes where parts must be cut from sheets of material; or *NGon* [7], which excels at converting complex meshes into NGon-based topologies, and can be highly effective for panelization as it supports rationalization of panels, enabling, therefore better segmentation for fabrication, ultimately improving material usage. Finally, *Compas Timber* [8] was introduced to manage complex timber joinery logic, allowing to automate the generation of cutting paths for materials with non-standard cross-sections.

2.3 Phase 3: Advanced Fabrication and Design for Disassembly (DfD)

The final phase focused on materializing the digital models using advanced manufacturing techniques. Based on the material, selected from the digital waste catalogue, students had to elaborate strategies for the remanufacturing of the material/components to fabricate their physical prototypes within 3 weeks of the course. The re-manufacturing/fabrication processes, therefore, together with the given constrained stock of materials, informed the design choices. Moreover, a core requirement was that

the structures had to be designed for disassembly (DfD) to ensure the materials could return to the cycle after their temporary use.

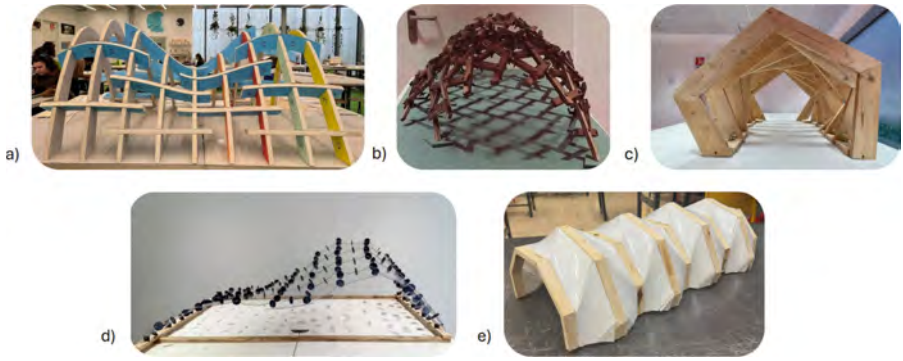


Fig. 2. Prototypes: a. The Skeleton; b. The Interlace; c. The twisting frame; d. the Polyhex; e. The Formilatte

3 Results

3.1 Structures

The course resulted in five full-scale structures (Fig. 2), each demonstrating a distinct strategy for operationalising waste.

The Skeleton addressed the challenge of "Material Agency." Dealing with moisture-swelled wooden panels that defied standard dimensions, they used the *Galapagos* evolutionary solver to optimize the nesting and placement of elements. Their script adapted the overall form of the pavilion to minimize cuts and waste, effectively letting the material dictate the design.

The Interlace built on appling reverse engineering to prototype a reciprocal shell. By initially overlapping and connecting a sample of carpenter's excess architectural moldings, the curvature that they produced was found and developed in repeating patterns to create a digital plan. By assigning lengths to cut from each section of stock using bin packing, minimal offcut waste was ensured.

The Twisting frame proved the value of data. This project relied on a rigorous ID-based catalogue that tracked quality and dimensions of wooden linear members, effectively turning a series of debris into a searchable "Temporary Material Bank." By combining *Phoenix* with *Compas Timber*, they could instantly query this bank to find the optimal piece for each structural member, minimizing cutting waste.

The Polyhex gave a completely unpredictable root to the waste generated during the production of polycarbonate panels. Four discarded panels were re-elaborated in hexagonal components connected through ad-3D printed bespoke PLA joints that fit perfectly, to allow spacing the hexagonal panels in a freeform configuration.

The Formilatte found a stream for the reuse of unconventional material coming from polypropylene cheese containers. Double-curved repeating surfaces were desired

as panels to fit across a frame structure, and so experimental molds were created from both cement and ABS. Using these molds, and a custom adaptation of a vacuum forming machine, large planar sections of the polypropylene containers could be re-formed into panels of higher geometric complexity.

Table 1. Likert graded survey questions.

Section	#	Question
Circularity & resource mapping	1.	I can now clearly distinguish between simple recycling and circular strategies (reuse/re-manufacturing).
	2.	I feel confident in performing "Digital Mapping" and cataloguing non-standard urban resources.
	3.	The course improved my ability to critically evaluate the reuse potential of discarded components.
	4.	I understand how to design for "Dry Assembly" and total reversibility of building components.
Digital design & advanced manufacture	5.	Computational tools were essential for adapting my design to the actual dimensions of the waste found.
	6.	3D printing was a critical enabler for solving complex interfaces between irregular materials.
	7.	Designing within the constraints of "available waste" led to more creative solutions than "free" design.
	8.	I can effectively bridge the gap between a digital model and physical fabrication (CNC/Robotics/3D Printing).
Pedagogical & professional outcomes	9.	Working in a multidisciplinary team helped me integrate different engineering and design perspectives.
	10.	Developing a physical prototype was essential to validating the digital and circular theories learned.
	11.	I believe "Digital Fluency" (computational skill) is a prerequisite for circular engineering.

3.2 Post Course Survey: Quantitative Feedback

To investigate the efficiency of the developed pedagogical framework a survey was developed that included Likert graded questions (on a scale of 1-5), as shown in Table 1. Figure 3 shows the results. Student responses indicated a significant increase in capability regarding the handling of non-standard resources. Students reported high confidence in performing digital mapping (Q2 avg.: 4.3) and strongly agreed that designing within the constraints of available waste led to more creative solutions (Q10 avg.: 3.7) than an unconstrained "blank slate" approach. Notably, there was a strong consensus that "Digital Fluency" is a prerequisite for circular engineering (Q8 avg. 4.4, Q11 avg.: 4.0), validating the course's heavy emphasis on computational skills (Grasshopper/Rhino) as a primary enabler of circularity. The lowest score was in Q8, suggesting the need to further develop skills in CNC and digital fabrication practice in future classes.

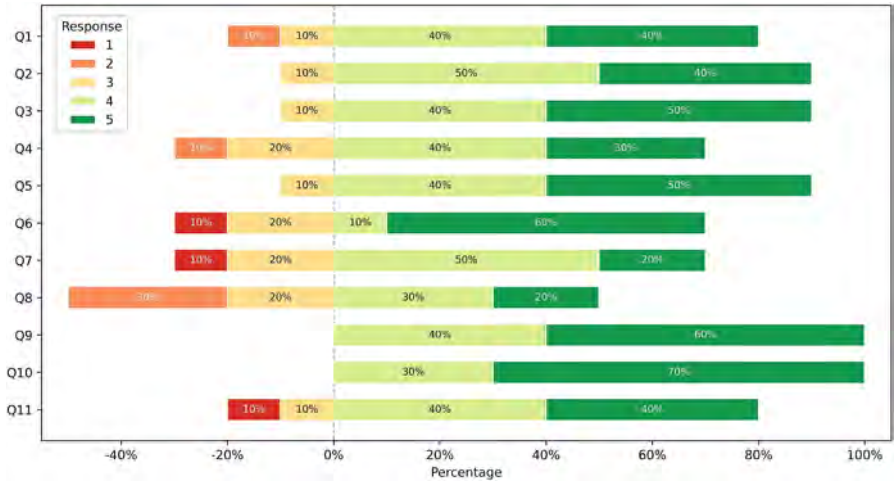


Fig. 3. Diverging stacked Likert chart of survey responses

Correlation between question scores were also calculated using Spearman's rank correlation coefficient. The highest correlation coefficients were Q6 vs. Q9 ($\rho = 0.964$), suggesting that technical challenges of 3D printing and adapting designs to best work alongside waste required technically varied teams; Q3 vs. Q11 ($\rho = 0.868$), indicating that those who felt they got better at seeing value in pre-used material stocks strongly believe that you need high-level computational skills to actually make that waste useful; and Q1 vs. Q4 ($\rho = 0.783$), suggesting that participants who grasped the conceptual difference between downcycling and circularity were significantly more likely to understand the technical benefits of reversible "dry" joints.

3.3 Post Course Survey: Qualitative Feedback

Additional open questions were also provided for each of the three sections, encouraging reflection on change in perspectives on material use, challenges in using digitised waste,

and the three-phase workflow of the pedagogy as an approach to prioritising circular material practices.

Open-ended responses highlighted a profound shift in perspective from linear consumption to circular adaptation. One student noted, *"*I stopped seeing materials as infinite products to buy and started considering them as precious resources already present in the territory."** Another described the workflow as an inversion of the traditional design hierarchy: *"*It is no longer the material that must satisfy a predefined form, but the design that adapts intelligently to the available resources."** However, the transition was not without friction; some students noted that strict adherence to "stock availability" could initially feel *"*limiting"** compared to traditional design freedom, highlighting the pedagogical need to frame constraints as creative drivers.

3.4 Case Studies: The Waste-to-Resource Matrix

The student reports for the structures were assessed to compare their material usage optimisation efforts. In the Skeleton, they noted that design utilised optimisation of nesting to adjust cutting patterns to best fit into the envelope of the cabinet boards they reused, leaving 38% offcut waste. In the Interlace, it was found using *Phoenix3D* and a custom evaluation component that a lower percentage of 15% of the architectural molding was left as offcuts. This groups use of metal fixtures was noted as a difficult item to source in the material catalogue, however the fixtures could enter the catalogue if and when the structure was assembled. Similar to the Interlace, the Twisting Frame utilised the same custom evaluation, leaving 33% of material as offcuts yet still with a high percentage of lengths which may be reasonably considered reusable.

With the Polyhex shell, moderate nesting of panels in the source material was applied but with a relatively high offcut waste of 59%, which could potentially have been improved through adjustment of the nesting parameters. The group additionally noted that the bespoke 3D printed connection components would be difficult to repurpose, although this was balanced somewhat by the biomaterial aspect of the PLA used. Finally, with Formilatte, they noted that 70% of the plastic trays used were effectively destroyed in the initial experimental prototyping stages, yet that now that the vacuum forming and molding process is honed future inefficiencies would be greatly reduced. For all of the groups, the initial setup of the communal material catalogue and the high use of dry assembly ensures that many parts of the structure, and the material stock offcuts, can be returned to the inventory for following cohorts.

4 Discussion

The results confirm that the barrier to reuse is often information, not material quality. By digitizing the waste (Phase 1), it becomes a "predictable" entity in the computational environment (Phase 2). This "Digital Twin" of the waste allows for high-precision fabrication (Phase 3) that would be impossible with manual methods. A key question remains regarding the scalability of this "Bespoke" approach. As one student noted, the shift from "Standard Catalogues" to "Urban Mining" is primarily a data management challenge. By developing robust scripts (like Group 05's *Compas* workflow), the "cost"

of dealing with irregularity drops significantly, making circular construction a viable alternative to the convenience of the linear model.

A recurring theme was the difficulty of "listening to the material." Traditional engineering creates a form and specifies a material to match. Circular engineering demands the reverse. The survey revealed that while students found this technically challenging (specifically managing tolerances), it was the key factor in changing their mindset. The "Informed" nature of the design - where the 3D scan data drives the geometry - ensures that the final structure is constructible despite the variability of the input.

4.1 Conclusion

This paper presented a "Waste-to-Resource" pedagogical framework that validates the use of computational workflows to bridge the gap between circular economy theory and construction practice. We demonstrated that Urban Mining combined with Computational Design transforms waste from a liability into a high-value asset. The successful fabrication of five reversible structures proves that when waste is digitized, it can be re-engineered with the same precision as virgin material. We conclude that Digital Fluency is not merely an optional skill but a fundamental prerequisite for the next generation of engineers tasked with building a regenerative future.

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Circular Education Pedagogies: Designing for Systemic Change

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Abstract. Integrating circular principles into architectural and engineering curricula requires pedagogies that create adaptive, responsive learning environments and support systemic understanding of circular value chains. Such models are crucial for enabling long-term transformation in the built environment and strengthening collaboration among key stakeholders. This contribution examines the potential of *case study* and *making* pedagogies to support circular education in architectural and engineering programs. It presents three educational settings implemented at TU Delft in which these pedagogies are applied among peer learners, learners and makers, and learners of different educational levels. The findings show that these learning environments foster knowledge production, collaborative structures and reflexive learning practices, helping students understand circularity as a systemic phenomenon rather than a purely technical challenge. Nevertheless, they require careful preparation, robust open educational resources, and active facilitation.

Keywords: circular education · pedagogy · built environment · systemic change

1 Introduction

Circularity focuses on extending the life cycle of both biotic and abiotic materials so that they remain functional for as long as possible. Moving beyond the linear "take–make–dispose" model, it promotes strategies such as reuse, repair, recycling, and redesign, often summarized through frameworks like the 10R hierarchy [1]. Beyond technical resource management, circularity represents a broader epistemic shift that challenges established relationships between materials, production systems, and societal practices. As such, it calls for new forms of knowledge production and learning that reflect the systemic, relational, and iterative nature of circular value chains.

Circularity is becoming critical in tackling Europe's carbon emissions, waste production, and material use. The development of regulations and policies such as the EU Circular Economy Action Plan [2] attest to EU's commitment to setting new standards for the reduction of the construction sector's impact. The CE has thus become a political priority [3] with governments such as the Netherlands committing to achieving a fully circular economy by 2050 [4].

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The ideas that circularity brings forward when operating at scale can have a significant impact on value chains, industries, and other networks [5]. The implementation of circularity thus requires systemic innovation and adjustment among all the relevant stakeholders, higher education institutions (HEIs) included [6]. For HEIs, this can happen in both research and education. The role of higher education is central to ensuring the systemic level transformation that is required for circular economy [7]. This is true for training both future professionals as well as the current workforce through LLL. The need for the latter is further exemplified by EU initiatives such as the NEB Alliance [8] and the proliferation of online learning offerings produced in the last decade.

Sustainability has found its way into curricula since the 1990s; however, for circularity, there is still a lot of ground to cover [9]. Despite current policy directives and research directions, the urgency of the climate crisis and materials depletion is not reflected in the speed of curriculum reform. Within the architecture, engineering, and construction (AEC) sector -one of the most resource-intensive and polluting sectors- education on circularity is still primarily framed as a technical problem addressed within disciplinary silos [10]. Such approaches often overlook broader environmental, social, and economic implications. They also frequently lack systems-level perspectives, leaving curricula ill-equipped to address the complexity of circular value chains and the intersections between material systems and social structures.

Circular education as a topic appears relatively late in the literature and remains underexplored [11]. A discourse on circular competences is ongoing [12]. For the rest, current literature on circular education identifies *two streams of action*: one that addresses the *lack of resources for educators* [13], and a second one that addresses the *lack of relevant pedagogies* [14].

This contribution focuses specifically on identifying the qualities for pedagogies that can support education for circularity. The following section examines the nature of knowledge in the circular paradigm; the challenges this is accompanied by and further identifies relevant matching pedagogies.

2 The Challenges and Opportunities in Teaching Circularity

Circularity is an elusive and evolving knowledge domain that challenges the foundations of our material perception, standardized production practices, and the relationships humans form with materials, infrastructures, and ecological systems. It manifests simultaneously across three key dimensions: a theoretical construct, a practical system, and a value framework. This multiplicity complicates its integration into education: how can educators encourage learners to embrace the otherness of circularity when its contours remain only partially defined? How can they support learners in translating circular principles into practice? And how can they cultivate resource responsibility through practices of care and sharing?

Circularity therefore requires forms of knowledge that are relational, experimental, and collaborative, qualities that pose particular challenges for traditional educational models. *Transdisciplinary learning* (TL) is one pedagogical approach relevant to the entangled nature of circularity because it integrates diverse perspectives and pushes the boundaries of established disciplines [15]. Furthermore, TL presupposes a systemic

change in basic teaching attitudes and understanding of didactics: it reduces teachers' control by dismantling hierarchies and extending to collective responsibility; it establishes reflective practices and feedback literacy; and further promotes research alliances of diverse but equal actors and about overcoming the rifts between university and society [15].

Multiple pedagogical formats can support transdisciplinary learning. This study focuses specifically on *Case Studies (CSs)* and TL *Making Pedagogies (MPs)*, which are particularly suited to the systemic and material nature of circularity. Together, these pedagogies allow circularity to be explored across its three key dimensions.

CSs refer to the investigation of a product, person, organization, or process characterized by complex circumstances [16]. The aim of CSs is first to gain a better understanding of the phenomenon by investigating and revealing its mechanisms and origins in its specific context, and then to derive lessons learned, which may be transferable to other and future cases.

MPs are common in AEC education as the 'doing devices' they rely on are easier to find and to apply [17]. MPs are valued in AEC education for their experiential, open-ended character, and their capacity to integrate both mind and body [18]. Being rooted in the real world, they rely on cross-disciplinary collaboration; therefore, knowledge is constructed not consumed, further contributing to MPs systemic character [19].

Both pedagogies have the potential to support systemic transformations. CSs derive their strength from their situated and contextual character, while MPs enable embodied forms of knowledge creation. This paper posed the question: How can CSs and MPs be applied to support circular education in the built environment?

3 Actualizing CSs and MPs

This study adopts a practice-based research approach to examine pedagogical strategies for circular education in the built environment. It investigates three educational settings within the Faculty of Architecture and the Built Environment (ABE) at TU Delft: (1) the Circular Design Atlas (CiDeA) assignment, (2) The Circular Product Design course (CPD), and (3) The Summer School on Circularity in the Built Environment (SS). The author was directly involved in the design and implementation of the three educational settings presented.

3.1 The Circular Design Atlas (CiDeA)

CiDeA [20] is an informal assignment distributed to all six hundred students of the Architecture Masters track (MArch 1) in the beginning of the first semester. Students are required to work in groups of four over a period of eight weeks with minimal guidance for their tutors. Considering the multiplicity of the interpretations of circularity at the building scale, this exercise aims at clarifying the dominant notions and aligning the terminology used. It also serves as inspiration. Students are required to analyze an existing building that has one or more circular characteristics following a template. The template is structured around eight sections. These include, the analysis of the building's *shearing layers*; the *building materials' origin*; the *embodied carbon calculation of 1*

m^2 of the building's façade; the *R strategies* considered in the building's making; its *integration in the local Nutrients-Energy-Waste* (NEW) *flows*; the principles guiding its *design*, an *analysis of the stakeholders* involved in the entire process; as well as an *overall reflection* on the level in which circularity was achieved. All sections are supported by open educational resources (OERs) -namely in the form of short videos- that match the template requirements. Upon submission, best case studies analyses are uploaded on an online database and made openly available to the greater learning community.

3.2 The Circular Product Design (CPD) Course

CPD is an elective course of the Building Technology Masters track (MSc1) with a duration of 10 weeks. It mainly focuses on the component scale. Almost **forty** students come together from the Master of Building Technology and the Master of Architecture of ABE. The course is divided into two parts: over the first four weeks, students receive input from 12–16 guests on the topics of materials, design, manufacturing, and management while they analyze an existing building product across these four domains and different applications (facades, floor or roof systems, walls, etc). For the second half, they are asked to design a closed building envelope using either biobased or reclaimed materials and then prototype 1:1 the most representative detail of that configuration. To do that, ABE students collaborate with students from ROCvA, a vocational school for carpenters. Results are shared through a report that documents all processes from conceptualization to prototype and reflects on the process and the end-result.

3.3 The Summer School (SS) on Circularity in the Built Environment

Lastly, the **SS** is a yearly event organized by the faculty's Circular Built Environment Hub (CBE Hub) around a topic related to one or more scales of the built environment. The event is open to students and professionals that are involved in the AEC sector and share an interest in the topic. In the later years, the duration of the summer school has been extended to one week during which, participants are required to collaborate on a hands-on project. In 2025, the overall theme was REUSE. The summer school offered structured discussions on the topic of REUSE, design workshops, prototyping sessions, as well as one final reflective presentation of the end results and the process. In addition, participants engaged in a public debate organized around the topic and ultimately compiled a manifesto for REUSE.

4 Lessons Learned from Applying Transdisciplinary Learning Pedagogies

The three educational settings presented above demonstrate different ways in which circularity can be operationalized in architectural and engineering education via CSs and MPs. The three examples explore different configurations of circular learning environments, including peer-to-peer learning, collaboration between learners and makers, and cross-level collaboration among students and professionals.

To analyze the pedagogical potential of the approaches discussed above, the research follows a qualitative comparative analysis. The analysis draws on multiple sources of evidence, including course documentation, assignment structures, student outputs, prototypes, and reflective observations from the implementation of the courses. The aim of the study is to identify pedagogical qualities that support systemic learning for circularity.

The three examples are examined through four analytical lenses: ***knowledge production***, referring to how theoretical and practical knowledge is generated; ***collaboration structures***, referring to how relationships between learners, makers, and institutions are organized; ***reflexivity***, referring to the mechanisms through which participants reflect on materials, processes, and decision-making, and *key pedagogical insights*. These lenses allow the cases to be compared and help identify qualities relevant for circular education. (Table 1).

Across the three cases ***knowledge production*** results from analytical investigation, material experimentation or a combination of both. Several observations indicate the high pedagogical value of CSs and MPs in knowledge creation: for CiDeA this is the increased rate of completion with almost all student groups submitting their analyses by 2025 and more than 30 best cases uploaded to the online platform per year (representing 25% of all students in the studio). Over time, the Atlas has evolved into a growing repository of case studies and an open learning resource for the broader educational community. For CPD, knowledge creation is demonstrated by the course completion rates and the quantity and quality of the student generated prototypes. In the past two years, several student prototypes have been exhibited in exhibitions and even featured in research publications. Lastly, for the summer school, both the generated manifestos and the physical prototypes attest to the high potential of learning even in rapid formats.

Taken together, ***collaborative structures*** demonstrate that circular education benefits from the inherent qualities of CSs and MPs to expand the learning environment beyond the traditional classroom, connecting learners with other knowledge communities and professional actors. For CiDeA, the peer-to-peer structure allows large cohorts of students to engage with complex circular case studies while maintaining a manageable workload. The cross-level and cross-sector partnerships for CPD allow students to experience circular design as a multi-actor process involving diverse forms of expertise. Over time, consistent collaboration with ROCvA students has led to improved quality in the prototypes produced. A similar dynamic is evident in the SS setup. Additionally, the SS challenges collaboration boundaries by bringing together students, researchers, and professionals in mixed cohorts, reflecting the interdisciplinary and multi-stakeholder nature of circular value chains in real time.

Collectively, the cases demonstrate that ***reflexivity*** manifests in the reporting and documenting of the learning experiences. The real success of CiDeA lies in the qualitative assessment of students' reflections where they are asked to assess the systemic character of circularity at the building scale. There it is often noted that they can acknowledge the complexity of stakeholders' interactions, identify instances of greenwashing, and even offer alternatives to strengthen circular performance. For CPD reflexivity occurs through iterative design reviews and documentation of the prototyping process. Students are required to reflect on both the conceptual and material implications of their design decisions, particularly when working with unfamiliar biobased or reclaimed materials. In

Table 1. Overview of the three pedagogical settings analyzed through the lenses of knowledge production, collaboration structures, reflexivity, and key pedagogical insights.

Pedagogical Setting	Knowledge Production	Collaboration Structure	Reflexive Mechanisms	Key pedagogical insight
CiDeA – Informal blended learning activity (CS)	Systematic analysis of existing circular buildings; students investigate material flows, design strategies, and circular principles in built case studies	Peer to peer collaboration. Almost 600 Master of Architecture students work in small groups with minimal supervision, supported by OERs	Structured analytical templates guide reflection on circular strategies, stakeholder interactions, and design decisions	Autonomous, peer learning environments can effectively develop systemic analytical understanding of circularity
CPD – Formal elective course (CS + MP)	Integration of analytical and experimental knowledge through product analysis, circular design, and 1:1 prototyping using biobased or reused materials	Peer-to-peer, cross-level, and academic–practice collaboration involving architecture students, vocational learners, and industry partners	Iterative design reviews and documentation of prototyping processes encourage reflection on material behaviour and design decisions	Combining analysis and making enables students to translate circular principles into practical design solutions
SS – Informal summer school (CS + MP)	Experimental exploration of reuse strategies through rapid prototyping and collaborative design exercises	Peer-to-peer, cross-level, and academic–practice collaboration in mixed cohorts of students, researchers, and professionals	Continuous feedback from tutors, industry experts, and peers supports reflection on material experimentation and design outcomes	Short, intensive learning environments can stimulate rapid collaborative exploration of circular design strategies

the Summer School, reflexivity is facilitated through continuous feedback from tutors, industry experts, and peers, as well as through collective reflection exercises such as public debates and the development of thematic manifestos.

5 Discussion

The analysis of the three examples demonstrates how CSs can support the development of systemic understanding, while MPs enable learners to test ideas through material experimentation within broader construction ecosystems. When combined, these approaches

create opportunities for learners to iteratively connect theory, practice, and values, three dimensions that are central to the circular paradigm.

Nevertheless, the integration of CiDeA took time to unfold and required funding to support the development of blended learning resources as well as tutor training sessions to ensure that instructors recognized the value of the activity and could effectively support it when necessary. As for CPD, course preparation is time-consuming, the effort required by tutors and students is significant, and students are exposed to a high degree of complexity. Similar considerations apply to the SS, which also requires thorough preparation and coordination.

Despite these challenges, the cases suggest that circular education benefits from learning environments that combine analytical inquiry, material experimentation, and collaborative engagement. Such environments enable learners to understand circularity as a systemic phenomenon rather than a purely technical problem. By exposing learners to diverse actors, material processes, and decision-making contexts, these pedagogical settings help develop the competences required to navigate the complex value chains involved in circular construction. CSs and MPs may also be transferable to other higher education institutions seeking to integrate circularity into design education, provided that adequate institutional support and cross-sector collaboration are available. More broadly, the findings indicate that designing education for circularity requires moving beyond traditional lecture-based formats toward learning environments that are exploratory, collaborative, and reflexive.

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Workshop Design for Circular Economy Business Models

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Abstract. This study investigates the optimal structure for a Circular Economy (CE) business model design workshop tailored for scholars. The objective was to create a framework that fosters active participation, bridges the gap between theoretical learning and practical application, and facilitates scholarly dissemination. Drawing on the CE theory, the workshop was designed around three pillars: Pedagogy and Engagement, Content Focus, and Time/Output Structure. The core methodology employed the Sustainable Business Model Canvas (SBMC) framework, requiring participants—primarily early-career researchers and PhD students—to analyze existing initiatives or propose new Circular Economy Business Models (CEBMs) through iterative co-design sessions. The workshop was tested in a CircularB Training School and successfully created a dynamic learning environment by balancing instructional styles with hands-on application. Integration with an academic conference enhanced the visibility of participant work, while peer-assessment and group presentations served as critical feedback loops.

Keywords: circular · business model · design workshop · Sustainable Business Model Canvas (SBMC)

1 Introduction

The construction industry is a major consumer of raw materials and a significant producer of waste, necessitating a shift from linear "take-make-dispose" models to circular approaches. COST Action CA21103 – CircularB aims to implement the Circular Economy (CE) in the built environment through international cooperation and knowledge sharing [1]. A critical component of this effort is the training of early-career researchers and PhD students to understand the relationship between resource consumption and waste production. This paper presents a framework for a CE business model design workshop, using the CircularB – 2nd Training School in Riga as a primary reference point.

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1.1 Learning Outcome and Competences of Training School

The designed learning outcome and competences of participants of the training school included:

- understand the relationship between resource consumption and waste production and can describe recent developments in the construction and real estate industry.
- can apply definitions and strategies for implementing the circular economy within their own contexts.
- can evaluate and interpret circular design / construction / use / operation principles for new and existing buildings and apply them to projects.
- are able to identify key factors that can be used to improve the circularity of both an existing building and one that is being planned.
- understand both the environmental impacts of different product/building phases and the best environmental assessment methods, as well as the benefits of these methods.
- are familiar with quantitative indicators used to assess circularity and the potential for waste prevention, understand how these are reflected in certification systems, and are able to apply them.
- gain practical experience in illustrating and optimizing the circularity of products.
- develop own sustainability and circularity business model

1.2 Key Features Throughout the Training

The following key features were maintained throughout the training:

- **Teaching/Learning Methods:** Lectures, Interactive instructions, Application Tasks, Case Studies, Exercises, Problem-based learning, Literature review
- **Interactive Workshops:** Emphasize was put on hands-on activities, group discussions, and case study analysis.
- **Practical Tools and Resources:** Provides participants with templates, guides, and online resources.
- **Real-World Case Studies:** Use of relevant and engaging case studies to illustrate key concepts.
- **Emphasis on Systems Thinking:** Helps participants understand the interconnectedness of circular systems.
- **Focus on Actionable Outcomes:** Ensures participants leave with practical knowledge and tools they can apply.
- **Expert Speakers:** we include industry professionals and researchers to share their insights.
- **Networking Opportunities:** Facilitates connections between participants.
- Established a link with a conference and LCA summer school in the same week.

2 Methodology: The Three-Pillar Framework

The training school is structured as a 4-day intensive workshop program that progresses from theory to dissemination:

- Day 1 (Foundations): Contrast of linear vs. circular models and introduction to emerging digital trends (Digital Twins, AI).
- Day 2 (Practical Tools): Hands-on exercises with simplified assessment tools and the mapping of material flows for urban mining.
- Day 3 (Action Planning): Group work dedicated to developing a circular business model, culminating in a pitching session to peers and experts.
- Day 4 (Innovation & Dissemination): Integration with an academic conference, such as IMST 2025, where results are presented and participants engage with industry professionals.

The inputs were delivered by an experienced teaching team consisting of eight international recognized scholars from various backgrounds ranging from Civil Engineering, Economics, to Architecture and Facility Management.

The workshop structure is defined by three interconnected pillars (namely pedagogy, content, and output structure) that ensure theoretical depth and practical relevance.

2.1 Pillar I: Pedagogy and Engagement

The framework prioritizes an on-site, interdisciplinary, and hands-on format. Effective scholarly engagement is achieved through a mix of teaching methods:

- Active Learning: Utilizing lectures, interactive instructions, case studies, and problem-based learning.
- Gamification: Integrating tools like the CEBM game to simulate business model innovation in a risk-free environment.
- Systems Thinking: Helping participants understand the interconnectedness of circular systems rather than viewing components in isolation.

2.2 Pillar II: Content Focus (The SBMC Framework)

The Sustainable Business Model Canvas (SBMC) serves as the core analytical tool. Participants must navigate eleven distinct elements to define a CEBM [2, 3]:

1. Sustainable Partners: Identifying cross-sector collaborations and industrial symbiosis.
2. Sustainable Value Creation: Focusing on activities like adaptive reuse and additive manufacturing.
3. Sustainable Tech & Resources: Prioritizing the substitution of virgin materials with bio-based alternatives like algae, hempcrete, or sheep wool.
4. Sustainable Value Proposition: Solving problems such as construction waste and resource depletion while creating customer value.
5. Sustainable Customer Relation: Building trust through transparency and performance dashboards.
6. Responsible Customers: Enabling customers to act sustainably through incentives and education.
7. Sustainable Channels: Using local supply chains and digital platforms (e.g., Building Information Modelling (BIM), QR tracking) to communicate sustainability.
8. End of Life: Designing for disassembly and profitable upcycling.

9. Cost Structure: Assessing the economic feasibility of sustainable alternatives.
10. Subsidization: Identifying tax bonuses and grants.
11. Revenue & Sustainability Premium: Developing pricing structures that incentivize sustainable behavior.

Figure 1 provides an overview of Sustainable Business Model Canvas (SBMC) which was used to design the CE models during the workshop.

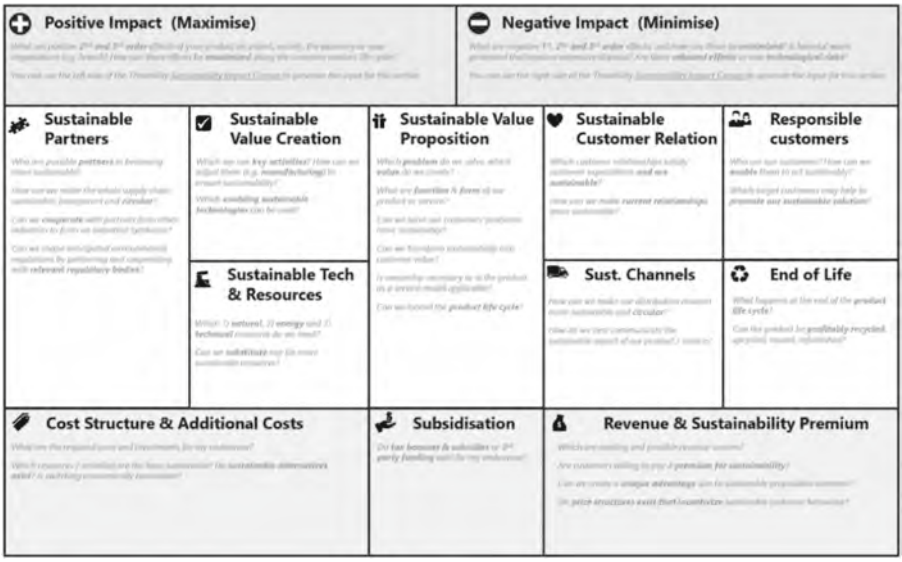


Fig. 1. Overview of Sustainable Business Model Canvas (SBMC) [2].

2.3 Pillar III: Time and Output Structure

The development of the CEBM was done in three steps.

- Step 1 (May 2025): Task list for your case study of a CEBM.
- Step 2 (Sep 2025): Training school with dedicated lectures and group work, group presentations of CEBM and feedback loops.
- Step 3 (Oct 2025): The groups were asked to finalize their CEBM in Synthesis report.

3 Application and Case Study Results

Drawing from the experience of the training school, the results can be described in the following elements: Quantitative Performance Metrics, Technical and Environmental Assessments, Business Model Analysis (SBMC Elements), Digital and Asset Documentation, Socio-Economic and Heritage Outcomes, Workshop and Training Outputs.

3.1 Quantitative Performance Metrics

The examples that were presented during the workshop frequently highlight specific, measurable outcomes that demonstrate the success of a circular approach:

- Circularity Indices: Documentation of the percentage of material reuse, such as the 50% material circularity achieved in one project.
- Carbon and Energy Reductions: Data showing the environmental impact, such as a 53% reduction in CO2eq-GWP and 58% less embodied energy through 3D printing and topology optimization.
- Waste and Emissions Data: Reporting on emissions-free construction sites (e.g., 90% emissions-free) or reductions in material volume (e.g., 60% reduction via topology optimization).

3.2 Technical and Environmental Assessments

Results often stem from rigorous analysis tools used during the project lifecycle:

- Life Cycle Assessment (LCA): Findings from "cradle-to-gate" or "cradle-to-grave" assessments that compare circular methods to conventional ones.
- Material and Mineral Analysis: Specific findings from laboratory studies, such as the X-ray fluorescence (XRF) analysis used to determine the mineral content of waste foundry sand.
- Resource Mapping: Results from mapping material flows to identify opportunities for urban mining or resource optimization.

3.3 Business Model Analysis (SBMC Elements)

A core result is the identification and specification of the eleven elements of the SBMC for a given project (Sect. 2.2). The discussions during the workshop focused in particular on:

- Value Propositions: Clearly defined environmental, social, and economic value created (the "Triple Bottom Line").
- Cost-Revenue Models: Summarized financial data, such as per-unit costs for land acquisition, construction, and annual operating revenues.
- Stakeholder Identification: Tables detailing key partners (authorities, investors, communities) and their specific contributions to the circular system.

3.4 Digital and Asset Documentation

Results include the creation of digital data repositories:

- Material Passports: Digital records of the characteristics, origin, and future reuse potential of materials.
- Digital Twins and BIM: Visualizations and data-driven models that track the conservation status or energy performance of a building in real-time.

3.5 Socio-Economic and Heritage Outcomes

Qualitative results that reflect broader community impacts are another essential part of the SBMC:

- Job Creation and Social Inclusion: Evidence of social value, such as providing work training for individuals with disabilities.
- Cultural Preservation: Documentation of how adaptive reuse has extended the life of historic assets by decades while maintaining cultural identity.

3.6 Workshop and Training Outputs

Since the results pertain to a design workshop or training school, they contain:

- Pitched Business Models: The final circular business models developed by groups during the session.
- Individual Action Plans: Personalized strategies created by participants for implementing circularity in their own professional contexts.
- Case Study Comparisons: Analyses of existing initiatives used to illustrate and optimize the circularity of new products or buildings.

4 Discussions

The analysis of the training school which involved CEBMs reveals several aspects regarding the implementation and viability of circularity within the Built Environment. The aspects of circularity, collaboration, and digital tools and design are important for successful strategies across economic, environmental, and technological dimensions, as well as necessary pathways for future scaling.

4.1 Key Aspect of Circularity

A fundamental conclusion across the case studies is that the Circular Business Model (CBM) is not merely a theoretical goal but a practical and profitable reality [5].

The training school provided a common understanding of successfully reframe waste or obsolescence as resource opportunities. Business Models focused on product longevity and service demonstrate clear long-term savings. Servicization models (e.g. FaaS) shifts costs from capital expenditure (CapEx) to predictable operational expenditure (OpEx), reducing the risk of obsolescence for the customer. The same is valid for financial incentives dimension. Subsidization and tax incentives are crucial elements of BMs for mitigating the higher upfront costs often associated with circular practices. It became clear that some BMs could be supported by municipal funding that provides a subsidy to the company to promote circular innovation (DfD) and reusable materials. Heritage projects often benefit from tax incentives offered for the preservation of cultural sites.

4.2 Collaboration and Policy Alignment Are Essential Drivers

The success of robust CEBMs relies heavily on multi-stakeholder collaboration and alignment with supportive government policies. This aspect was fostered in the workshop by providing interdisciplinary teams and the forum to discuss multi-stakeholder collaboration. E.g. a Waste Heat integration model applied a Public-Private Partnership that links the digital sector (data centres) with energy utilities (district heating). Similarly, the Foundry Sand model relies on establishing a "mutual gain" system (win-win) between two different industrial sectors. Another aspect of SBM is the social and community value of CEBM that integrate social benefits, such as job creation or community resilience. If the SBM enhances community resilience and provides social inclusion programs alongside environmental metrics this goes considerably beyond CEBM.

4.3 Digital Tools and Design Principles

We saw that in all groups Digital Tools and Design Principles define modern Circularity. Digitalization and specific design methodologies (like Design for Disassembly) are fundamental enablers for managing resources throughout their extended lifecycles. Digitalization also enables traceability and effective management of resources. BIM was central to some BMs, providing data infrastructure to document material characteristics, origin, and future reuse potential. In some cases, smart tracking and QR codes were proposed for modular components to simplify maintenance and facilitate reuse networks. In essence, digital platforms were used to create transparent markets for salvaged materials. Design for Disassembly and Modularity are key technical adjustments that guarantee material reuse and adaptability. And the shift extends beyond recycling to regenerative approaches.

The workshop functions as a "circular resource hub" where raw research ideas are refined through iterative co-design [4]. For example, a student's interest in heritage could be processed through the SBMC into a sophisticated plan for retrofitting abandoned houses in Esfahan into sustainable hotels. Peer-assessment and coaching from expert trainers serve as the "refinement" stage of the hub, ensuring that the final "intellectual assets"—such as individual action plans or conference presentations—are of high quality. To maximize scholarly impact, the workshop must align with external publishing cycles, such as Scopus-indexed proceedings, providing a tangible academic return on investment for participants.

5 Conclusion

Designing a workshop for CE scholars requires a transition from traditional teaching to a collaborative, output-driven framework. By anchoring the workshop in the three pillars of pedagogy, SBMC-based content, and conference-aligned structure, educators can ensure that practical outputs evolve into significant scholarly contributions. Such workshops are essential for bridging the gap between theory and the implementation of circularity in the built environment.

The optimal structure for a CE business model design workshop for scholars relies on the balance between pedagogical engagement, the structured application of the SBMC,

and a timeline that culminates in scholarly dissemination. By strategically aligning these workshops with academic conferences, organizers can transform theoretical knowledge into actionable, publishable contributions that accelerate the transition to a circular built environment.

We identified several shared needs for future investigation to accelerate the circular transition: Future CEBM research must (1) focus on developing quantitative frameworks to measure the long-term environmental and financial performance of CEBMs, including long-term cost savings from material reuse and lifecycle carbon analyses; (2) examine the replicability of successful models across diverse building typologies, regulatory environments, and geographic locations; (3) advance digital integration; (4) identify incentives that accelerate market adoption and standardization within circular construction ecosystems.

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Developing Innovation Competencies in Engineering Education for Sustainable Transitions: The InnoVerse Bootcamp Case

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Abstract. Engineering education is increasingly expected to prepare students with the innovation competencies needed for sustainable transitions in industry and the built environment. This paper examines InnoVerse, an innovation bootcamp developed at the Faculty of Engineering, NTNU, as a pedagogical response to the need for stronger innovation competencies, interdisciplinary learning, and sustainability-oriented problem-solving in engineering education. The study adopts an exploratory case-study approach and analyses two four-day bootcamp editions organised across NTNU's three engineering campuses. InnoVerse brought together bachelor's and master's students to work in interdisciplinary teams on authentic, industry-defined challenges related to sustainability, construction, the environment, maritime innovation, and energy efficiency. Data were collected through programme documents, participation records, and anonymous post-bootcamp questionnaires. The findings indicate that the bootcamp contributed positively to students' perceived development of innovation-related and transversal competences, particularly teamwork, communication, networking, industry awareness, and engagement with open-ended industry challenges. The study further identifies conditions for improving such formats, including clearer challenge framing, structured mentoring, stronger curricular embedding, and sustained collaboration with industry partners.

Keywords: Skills · Innovation · Sustainable transformation · Engineering education · Built environment · Bootcamp

1 Introduction

Universities play a crucial role in fostering innovation by integrating innovative pedagogies, advanced technologies, and adaptive leadership practices that collectively create dynamic learning environments [1, 2]. These environments enhance students' innovation competencies by encouraging creative problem-solving, critical thinking, and interdisciplinary collaboration. Key initiatives such as experiential learning activities, hackathons, design thinking workshops, and targeted faculty development programs are vital for overcoming institutional barriers and nurturing a sustainable culture of innovation.

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Innovation is increasingly recognised as a cornerstone of higher education's mission to prepare students for complex, rapidly changing global challenges [3, 4]. The capacity to innovate—encompassing creativity, critical thinking, collaboration, and adaptability—is essential for graduates entering a workforce shaped by technological disruption, sustainability imperatives, and societal transformation [5]. Universities are uniquely positioned to cultivate these competencies through dynamic learning environments, interdisciplinary curricula, and engagement with external partners, thereby acting as engines of both individual and societal advancement [2, 6].

Developing students' innovation competencies requires a multifaceted approach combining pedagogical innovation, technology integration, and experiential learning [7–9]. Approaches such as design thinking, cooperative learning, gamification, collaborative inquiry, flipped classrooms, and case-based learning are effective in developing innovation competencies. These methods foster creative and reflective thinking, bridging academic knowledge with real-world application [4, 10] and equip students with the competencies to address global challenges.

Bootcamps and innovation activities have emerged as effective methods for teaching sustainability by combining experiential learning, interdisciplinary collaboration, and practical problem-solving. Bootcamps provide immersive, hands-on learning experiences that focus on sustainability challenges [11].

Within the Faculty of Engineering at the Norwegian University of Science and Technology (NTNU), a strategy was established to increase students' innovation competencies, facilitate the development of solutions that contribute to sustainable environments, and introduce new actions. The faculty aimed to advance infrastructure, networks, and partnerships to create new models for accelerating transformation. One of these newly established activities was the InnoVerse, the Innovation bootcamp. We will explore the development, implementation and evaluation of the InnoVerse in two editions, following the research questions:

1. To what extent do the bootcamp activities contribute to increasing innovation competencies for students at the Faculty of Engineering?
2. What measures can be envisaged for bootcamp and similar activities to bring better outcomes for engineering programs?

This paper addresses these problems by examining the NTNU Faculty of Engineering's innovation ecosystem. Drawing on the innovation strategy documents, the 2021–2025 innovation strategy report, and the bootcamp programs and presentations, the study identifies both strengths and gaps in the education program's approach to supporting and developing students' innovation competencies. Key areas explored include promoting industry-academia collaboration, developing sustainability solutions through student and industry engagement, addressing industry challenges, and establishing sustained engagement with pressing societal issues. The findings aim to provide insights into how these types of innovation activities can better align to maximise societal impact and develop sustainable solutions for both the users and the environment.

2 The context of Innovation Competencies Endeavours

A central challenge for engineering education is aligning curricula with rapidly changing labour-market needs. Skills mismatches persist when graduates lack practical, interdisciplinary, and innovation-oriented competencies. Competency-based education offers a relevant response, although its implementation is often constrained by disciplinary traditions, conventional pedagogies and institutional resistance to curricular change [12, 13].

Technological advancement represents both a challenge and an opportunity in this landscape. Strategically embedded, technology can support experimentation, interdisciplinary teamwork, and problem-based learning, all of which are essential conditions for the development of innovation competencies [14]. In this respect, innovation bootcamps and similar activities could serve as important vehicles for combining technological engagement with challenge-driven learning.

Sustainability can be taught through bootcamps and innovation activities when it is approached not as an additional thematic module, but as a competence-based, action-oriented, and interdisciplinary learning process. This aligns closely with the challenges described above: higher education institutions are under pressure to respond to labour-market change, diversify learning approaches, integrate technology effectively, and build stronger external partnerships. In this context, Education for Sustainable Development (ESD) defines sustainability learning as the development of knowledge, skills, values, and the capacity to take informed individual and collective action on issues such as climate change, resource use, inequality, and biodiversity loss [15].

From this perspective, bootcamps provide a particularly suitable pedagogical format as they compress learning into intensive, collaborative, and challenge-driven experiences. Rather than teaching sustainability solely through lectures, bootcamps can engage learners in working on authentic societal or organisational problems that require them to analyse complex systems, negotiate values, imagine alternative futures, and design feasible interventions. This pedagogical logic resonates with the sustainability competence frameworks in higher education, especially the emphasis on systems-thinking, anticipatory, values-based, strategic, and interpersonal competences. Brundiers et al. [16], building on Wiek et al. [17], describe these as core competences for sustainability problem-solving, while UNESCO emphasises that ESD must move learners toward decision-making and action. In other words, sustainability is most effectively taught when students are asked not only to understand problems, but also to respond to them collectively. Bootcamps promote transversal skills like adaptability, collaboration, and interpersonal communication, which are critical for addressing complex societal issues [18].

For several years, NTNU had been developing an innovation ecosystem with a broad perspective. At the end of 2020, the strategy for the future had a clear orientation: sustainability, green transition and digitalisation; getting business and industry up and running after the pandemic; innovation in the public sector; and competence and work relevance in the education sector. The university incorporated clear strategies and measures to achieve the innovation goal, highlighting and increasing innovation activity to foster sustainable innovation originating in clusters and centres (NTNU report, Årsplan 2022). The Faculty of Engineering set the goal of developing an Innovation Ecosystem by

establishing a robust system for innovation and activities grounded in existing competencies and a culture of innovation. The ecosystem aimed to support activities that foster innovative thinking, increase the visibility of opportunities, and deliver value to society.

To respond to the need for the innovation ecosystem at the faculty, new skills and competencies for students, we decided to implement the following pedagogical strategy: 1) identify the competencies needed for students to fit the industry and job market needs; 2) the bootcamp methodology was selected as an appropriate learning strategy to provide students from different disciplines and study cycles with a shared learning experience; 3) a programme was designed to create a learning environment in which students could develop competencies regarded as essential for industry employability; 4) activities carried out and evaluated.

3 Methodological Framework

The Innovation BootCamp - InnoVerse was conceived to foster the development of new mindsets through industry–academia collaboration. This study adopts an exploratory case-study approach to examine the design, implementation, and evaluation of InnoVerse. The case-study approach was considered appropriate because the aim of the study is not to produce generalisable evidence of competence acquisition, but to analyse how an intensive, challenge-based learning format may support students' perceived development of innovation-related and transversal competencies in an engineering education context.

In this setting, industry partners introduced real-world challenges related to sustainability, construction and the environment. An important characteristic of InnoVerse was its cross-campus dimension, as bachelor's and master's students were recruited from the three campuses of the Faculty of Engineering, located in three different cities and representing diverse profiles within engineering and construction-related fields, including civil engineering, marine engineering, manufacturing, and new and renewable materials and technologies. It offered an intensive, hands-on experience where students engaged in real-world problem-solving alongside industry partners, working in interdisciplinary teams, rotating with a new focus each year and a new campus each year. It was organised by researchers from the Faculty of Engineering, in collaboration with Start NTNU and industry partners. The desired number of students from each campus was 10, resulting in 30 students per edition. The first event, held in 2023 in Ålesund, had the theme "Maritime Innovation Bootcamp", and the second, held in 2024 in Gjøvik, had the theme "Innovation for Lower Energy Consumption in Production". For 2025/2026, Campus Trondheim is set to host the next bootcamp.

Data were collected from multiple sources: bootcamp programme documents, participation records, post-activity evaluation questionnaires, and students' open-ended feedback. After each bootcamp, all participants were invited to complete an anonymous evaluation questionnaire administered through Nettskjema. Students were informed that the feedback could be used for evaluation and research purposes. In 2023, 18 of the 30 participants completed the questionnaire, and in 2024, 10 of the 12 participants completed it. The questionnaires included both closed-ended (rate from 1 to 10) and open-ended questions. The evaluated dimensions included practical arrangements, facilitation, relevance of the case or topic, usefulness of methods and tools, group dynamics,

programme sessions, and overall impression. The bootcamp methodology was the pedagogical response to the need for stronger innovation competencies, and the programme comprised four days of short lectures, teambuilding exercises, innovation methods, mentorship from academic and industry experts, and access to resources such as laboratory materials, business consultations, use cases, and industry visits. Throughout the bootcamp, students worked collaboratively in interdisciplinary teams to develop and present their solutions. The bootcamp ended with a final presentation where teams showcased their minimum viable solutions to a panel of academic and industry judges. The winning solutions had the potential for further development in collaboration with industry partners, offering students tangible career and research opportunities.

The findings were then interpreted in relation to the intended pedagogical objectives of InnoVerse: strengthening students' innovation competencies, supporting sustainability-oriented problem-solving, increasing exposure to industry challenges, and identifying measures for integrating bootcamp-based learning into engineering programmes. The limitations include that the evaluation is based on post-bootcamp student feedback; the findings reflect participants' perceived learning and experiences rather than measured competence development over time; the sample size was relatively limited and differed between the two editions.

4 Findings

This section presents the main results of InnoVerse's implementation across its first two editions.

4.1 Participation and Evaluation of the InnoVerse

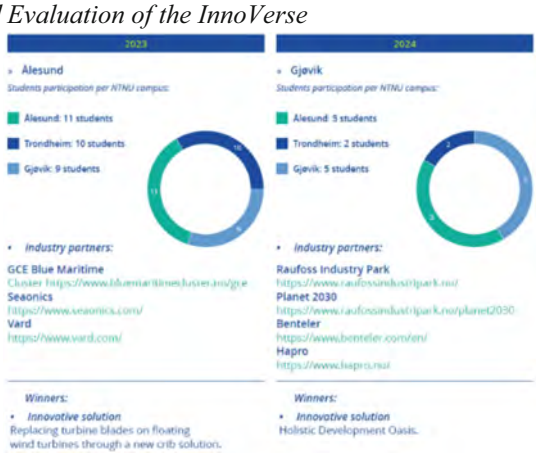


Fig. 1 InnoVerse participation per edition and per campus

The target was achieved in the first edition, held in Ålesund in 2023, which enrolled 30 students in total, distributed relatively evenly across campuses. Participation in the second edition, held in Gjøvik in 2024, was lower, but the distribution across the campuses remained similar, as shown in Fig. 1.

Across both bootcamp editions, the student evaluations indicate a predominantly positive overall experience. In the 2023 edition, overall ratings ranged from 7 to 10, with the largest share at 9 and 10. Similarly, in 2024, the overall assessment was also highly positive, with most responses again clustered at the upper end of the scale and more than half of respondents assigning the highest score.

4.2 Comparison Between the Two Editions

The comparison (Fig. 2) shows a consistent positive pattern across the two editions and identifies areas for improvement.

Dimension	2023 Maritime Innovation Bootcamp, Ålesund	2024 Lower Energy Consumption in Production, Gjøvik	Comparative interpretation
Recruitment, communication and practical organisation	+Students became aware of the bootcamp mainly through social media, teachers, other students, and information screens. - Long travel, food restrictions.	+Students heard about the bootcamp through teachers, Start, other students, information screens, and social media. - Stronger promotion, travel info.	Both editions show that communication and logistics are important conditions. → Improve early promotion and provide practical info earlier.
Facilitation and programme structure	+Presentations, teambuilding, industry visits, communication sessions, final event, and awards - Time for group work.	+Facilities, industry visits, teamwork, and final presentation format. - Not clear on final delivery task.	Facilitation was strong. → Balance input with sufficient work time, clearer milestones toward the final presentation.
Challenge framing and topic relevance	+ Case study. - Tasks overlapped, were too broad, or were too closely linked to specific companies.	+ Case study. - Missing precise expectations, narrower topic boundaries, and information about what was expected from the group.	Authentic industry challenges were valued in both editions. → Clearer challenge framing and expected output from the student work.
Methods, tools, and mentoring	+Methods and tools were generally useful; mentoring was appreciated. - Mentors redirected teams too strongly, more time to apply the learnings.	+Methods, design thinking, tools appreciated; mentoring was very good. - Not enough time to work before various rounds of mentoring.	Innovation methods and mentoring were important pedagogical components. → Link methods with the learning outputs and final delivery; train mentors.
Group dynamics, industry engagement, and perceived outcomes	+Working across campuses, countries, backgrounds; company visits, industry insight, networking, teamwork, creative work, learning about maritime challenges.	+Teamwork, meeting people, industry insight, mentor support, business contact, and the opportunity to challenge themselves.	Across both editions, the strongest perceived outcomes: interdisciplinary teamwork, industry engagement, networking, and exposure to authentic sustainability-related challenges.

Fig. 2. Comparative evaluation of the 2023 and 2024 InnoVerse bootcamp editions across selected programme dimensions.

5 Discussion

Overall, the findings indicate that InnoVerse is a promising pedagogical format for innovation-oriented engineering education, in that it brings together interdisciplinary teamwork, industry engagement, case studies, and solution development in an intensive learning setting.

RQ1. To what extent do the bootcamp activities contribute to increasing innovation competencies for students at the Faculty of Engineering?

The evidence suggests that the bootcamp contributes positively to students' perceived development of innovation-related and transversal competences. The strongest effects appear in interdisciplinary collaboration, communication, teamwork, networking, industry awareness, and the ability to work on open-ended challenges. Students consistently

valued collaboration with peers from other campuses and disciplines, engagement with real industry cases, and the opportunity to develop and present minimum viable solutions. These elements indicate that InnoVerse supports dimensions of innovation competence that are often difficult to cultivate through conventional lecture-based teaching alone. For example, the 2024 results further indicate that teambuilding activities and structured methods of the Triple Diamond design thinking methodology were generally perceived as useful, even if some elements were also experienced as demanding.

RQ2. What measures can be envisaged for bootcamp and similar activities to bring better outcomes for engineering programmes?

The findings suggest that the use of industry-defined challenges provides students with access to authentic problems and sets expectations that their work should lead to valuable, practically relevant solutions, rather than purely conceptual exercises. In this respect, the emphasis on developing and presenting minimum viable solutions appears especially important, and the possibility that winning teams may continue to develop their ideas with the company that owns the challenge creates a clearer bridge between student work and its external application. The continued provision of academic and industry mentors also remains important, and clear mentor training before the role is assumed should be introduced. In addition, students need sufficient industry input before selecting or narrowing the problem, followed by independent group work time. The final presentations appear to strengthen students' ability to translate ideas to mixed academic–industry audiences. More broadly, the bootcamp may offer greater educational value when it addresses topics not typically foregrounded in the regular curriculum, as several students valued the opportunity to engage with unfamiliar industrial problems and forms of creative work that contrasted with routine academic tasks.

In the built environment and construction-related engineering fields, such pedagogical formats are particularly relevant because sustainable transitions require graduates who can work across disciplines, engage with industry-defined problems, and develop solutions related to resource efficiency, energy use, circularity, and environmental performance. The faculty aimed to advance infrastructure, networks, and partnerships to support sustainable transformation in engineering education, including construction-related fields, where energy efficiency, resource use, circularity, and industry collaboration are increasingly central.

6 Conclusion and Paths Forward

The findings suggest that InnoVerse has clear practical potential as a challenge-based, industry-engaged learning format that can meaningfully contribute to the development of students' innovation competencies in engineering education. The bootcamps, such as InnoVerse, are most valuable when they are embedded more systematically within engineering programmes, linked to real industry challenges and societal needs, and supported by clearer long-term structures for recruitment, continuity, and follow-up.

While bootcamps and innovation activities are effective, challenges such as navigating institutional bureaucracy and aligning bootcamp outcomes with industry and society's needs remain. In this respect, the transition of InnoVerse into a 2.5 ECTS elective course represents an important step toward strengthening its educational legitimacy

and its potential as a sustainable model for innovation and sustainability learning in higher education.

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Influence of Urban Vegetation Levels on Women's Well-Being: A Virtual Reality Exposure Pilot Study

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Abstract. Urban vegetation has developed an important role in discussions about resilient infrastructure in the context of climate change. Given its many indispensable contributions to the proper functioning of cities, as well as the positive effects of viewing nature on psychological function, Urban Green Spaces (UGS) help mitigate human stress and restore physical and emotional well-being. The biophilia hypothesis demonstrates that, when appropriately integrated, reconnecting humans with nature promotes and enhances well-being. Brazil has high rates of anxiety, especially among women, who often face double work shifts and gender-specific health conditions. Therefore, this research is a pilot study that aimed to evaluate the impact of urban scenes with different levels of vegetation on stress and affective responses among women undergoing health treatment. The methodology involved simulated exposure to green spaces through virtual reality (VR) and the application of the State-Trait Anxiety Inventory and Positive and Negative Affect Schedule. We recruited 36 women undergoing health treatment at the Physiotherapy Center of the Federal University of Espírito Santo, Brazil. Participants were randomly assigned to view one of three 5-min VR videos of urban scenes with different levels of vegetation: an urban park (high vegetation), a public square (moderate vegetation), and a car-oriented street (low vegetation). The results indicated that scenes with greater vegetation, such as the urban park, produced a greater reduction in stress level and negative affect (NA) and an increase in positive affect (PA), highlighting the importance of vegetation and the incorporation of urban green spaces in promoting psychological health.

Keywords: Green Space · Virtual Reality · Well-being · Women's Health

1 Introduction

Brazil faces a growing mental health crisis, with record numbers of work absences due to mental health issues, particularly anxiety among women [1, 2]. Women demonstrate significantly higher prevalence rates of anxiety (1.6 times higher than men) and common mental disorders (3.75 times higher), reflecting critical gender disparities in mental

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health [3, 4]. The female population faces multiple challenges that corroborate this vulnerability, including the double work shift (professional and domestic), low professional gratification, and gender specific health conditions.

Studies have demonstrated the importance of human contact with nature in promoting well-being and reducing anxiety symptoms. An analysis of 10,749 participants from the Adults' People and Nature Survey revealed that women benefit significantly more than men from visits to green spaces [5]. The biophilia hypothesis postulates that humans have an innate biological connection with nature, and that natural environments promote emotional stability, attention restoration, and stress recovery [6–8]. Natural elements activate the parasympathetic system, leading to reductions in blood pressure, heart rate, and cortisol levels, thereby inducing relaxation and stress reduction [7].

The Positive and Negative Affect Schedule (PANAS) has been widely used in environmental psychology to measure affective responses to different environments. Similar studies utilizing PANAS have demonstrated that exposure to natural environments, even through virtual reality, significantly increases positive affect and decreases negative affect when compared to urban environments lacking vegetation [9, 10]. These findings align with the premise that contact with nature, plays a crucial role in emotional regulation and well-being. This research is a pilot study that aimed to evaluate the impact of urban scenes with different levels of vegetation on stress and affective responses among Brazilian women undergoing health treatment.

2 Methodology

2.1 Experimental Campaign

This pilot study was conducted at the Health School, located on the Maruípe campus at the Federal University of Espírito Santo (UFES), Vitória, Espírito Santo, Brazil (20°17′56.6″S, 40°18′56.7″W). This clinical facility encompasses multiple health-related academic programs alongside the University Hospital (Hucam). Recruitment was conducted between June 11 and August 8, 2025, resulting in thirty-six women. These participants were invited to join the study during their scheduled appointments at the Women's Health Physiotherapy sector at the Health School.

Participants were randomly assigned to view one of three 5-min VR videos, of urban scenes from the city of Vitória/Brazil, of which represented different levels of urban vegetation: Scene 1 (low vegetation) consisted of a car-oriented street; Scene 2 (moderate vegetation) consisted of a public square; and Scene 3 (high vegetation) consisted of an urban park (see Fig. 1). During data collection, two researchers were present where one was responsible for exhibiting the scene on the virtual reality (VR) headset and the other for the application of the questionnaire. Following the signing of the informed consent form, psychological indicators were evaluated using the StateTrait Anxiety Inventory (STAI) and the Positive and Negative Affect Schedule (PANAS). These measurements were taken before and after a 5-min VR exposure.

2.2 STAI and PANAS

To objectively measure the benefits of biophilic design, we used psychometric instruments that evaluate the impact of the environment on users' emotional states. We



Fig. 1. (a) Participant wearing virtual reality glasses viewing a urban scene randomly selected. (b) Urban scenes.

employed the State Trait Anxiety Inventory (STAI) and the Positive and Negative Affect Schedule (PANAS), both questionnaires validated in research in Brazil.

The STAI is a self-report questionnaire measuring trait and state anxiety. For this study, we utilized the reduced STAI-6 version [12] to evaluate the State Anxiety Scale (S), understanding how participants felt at the specific moment of application. The STAI-6 consists of 3 positive items (calm, relaxed, content) and 3 negative items (tense, upset, worried), evaluated on a 1 to 4 scale. Positive items are reverse-scored, and the sum indicates the current state anxiety level. The PANAS assesses levels of Positive Affect (PA) and Negative Affect (NA) [11, 13, 14]. The scale consists of 10 items for PA (e.g., excited, enthusiastic) and 10 for NA (e.g., distressed, nervous). Participants indicate the intensity of each emotion on a 5-point Likert scale. PA and NA scores are calculated separately by summing the respective items (range 10-50), with higher scores indicating greater affect intensity. Group means were then calculated for comparison across scenes. All procedures have approval from the human Research Ethics Committee of Federal Espírito Santo University, with a appreciation number CAAE n° 81840124.3.30001.5060.

3 Results

Before assessing the effect of virtual vegetation across the different scenes, a repeated measures ANOVA was conducted to examine the presence of statistically significant differences in the data. Time (pre and post exposure) was considered a within subject factor, and scene type a between subjects' factor, for both state anxiety scores (STAI) and positive and negative affect assessed by the PANAS. For the STAI, a significant main effect of time was observed ($F(1, 33) = 6.44$; $p = 0.016$), indicating a reduction in anxiety levels after exposure, regardless of the type of scene presented. No significant main effect of group was found ($F(2, 33) = 0.77$; $p = 0.470$), nor a significant time x group interaction ($F(2, 33) = 1.36$; $p = 0.271$), suggesting that changes in anxiety scores over time occurred similarly across scenes. These results show that the use of virtual reality, regardless of the urban setting, proved positive in reducing anxiety for the patient who was in the waiting room awaiting her physiotherapy appointment (Table 1).

Regarding positive affect (PANAS), no significant main effect of time was observed ($F(1, 33) = 0.12$; $p = 0.736$), nor was a significant main effect of group ($F(2, 33) = 1.16$;

Table 1. Results of the mixed-design ANOVA for STAI scores

Effect	df	F	p
Time	1, 33	6.44	0.016
Group	2, 33	0.77	0.470
Time × Group	2, 33	1.36	0.271

A mixed-design ANOVA was conducted with time (pre- and post-exposure) as a within-subject factor and group (scene type) as a between-subjects factor.

$p = 0.325$). However, a significant time × group interaction was identified ($F(2, 33) = 3.56$; $p = 0.040$), indicating that changes in positive affect over time differed according to the type of scene presented (Table 2).

Table 2. Results of the mixed-design ANOVA for Positive Affect (PANAS)

Effect	df	F	p
Time	1, 33	0.12	0.736
Group	2, 33	1.16	0.325
Time × Group	2, 33	3.56	0.040

A mixed-design ANOVA was conducted with time (pre- and post-exposure) as a within-subject factor and group (scene type) as a between-subjects factor.

Finally, for negative affect, the results indicated a significant main effect of time ($F(1, 33) = 15.50$; $p < 0.001$), evidencing a reduction in negative affect levels after exposure. No significant main effect of group was observed ($F(2, 33) = 0.43$; $p = 0.652$), nor was a significant time × group interaction found ($F(2, 33) = 1.00$; $p = 0.378$), indicating that the decrease in negative affect occurred similarly across the different scenes. Thus, it can be observed that the use of virtual reality, regardless of the scene, reduced anxiety and negative affect, proving to be a therapeutic treatment option that can be used. However, it is important to note that the type of scene influenced the increase in positive affect in the patients (Table 3).

Considering that no statistically significant differences were identified between the scenes, the graphs presented below have a descriptive and exploratory character, allowing the visualization of trends and variations in the data. Based on the analysis of the pre and post-exposure STAI boxplots, it can be observed that, in line with the ANOVA results, all three scenes were associated with reductions in participants' anxiety scores. Visually, scenes 2 and 3, corresponding to medium and high vegetation density, respectively, showed more pronounced decreases in anxiety levels when compared to scene 1, characterized by low vegetation density (see Fig. 2).

Regarding positive affect assessed by the PANAS, the pre and post exposure boxplots indicate a pattern like that observed for anxiety. Visually, scene 1 shows a modest

Table 3. Results of the mixed-design ANOVA for Negative Affect (PANAS)

Effect	df	F	p
Time	1, 33	15.5	<0.001
Group	2, 33	0.43	0.652
Time × Group	2, 33	1	0.378

A mixed-design ANOVA was conducted with time (pre- and post-exposure) as a within-subject factor and group (scene type) as a between-subjects factor.

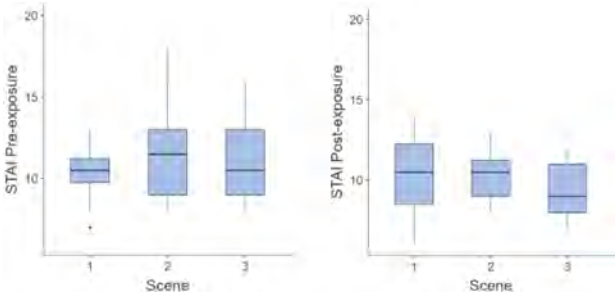


Fig. 2. Boxplots of pre and post exposure STAI-S scores. Scene 1 (low vegetation density), Scene 2 (medium vegetation density), and Scene 3 (high vegetation density). Boxes indicate interquartile ranges, horizontal lines represent medians, and whiskers indicate score dispersion.

increase in positive affect scores, suggesting a lower impact on the intensification of these emotions. In contrast, scene 2 exhibits a more pronounced increase in scores during the post exposure period, while scene 3 demonstrates the most consistent performance among the three conditions, with higher medians and a more concentrated distribution after exposure. This pattern suggests that scenes with greater vegetation presence tend to more strongly promote increases in positive affect (see Fig. 3).

For negative affect assessed by the PANAS, a pattern distinct from that observed for positive affect is evident. Overall, all three scenes show reductions in negative affect scores from pre- to post-exposure, indicating a global effect of exposure. However, scene 2, corresponding to medium vegetation density, presents the least favorable pattern among the three conditions, with more modest reductions in scores. Scene 1 shows an intermediate pattern, with a more noticeable decrease in negative affect, whereas scene 3, characterized by higher vegetation density, again demonstrates the most consistent results, with lower medians and a more concentrated distribution in the post-exposure period (see Fig. 4).

The descriptive analysis of the STAI items suggests that the reduction in anxiety observed in the total score is associated with increases in positive emotional states, such as calmness and relaxation, and decreases in negative states, such as tension and worry, particularly in scenes 2 and 3 (see Fig. 5).

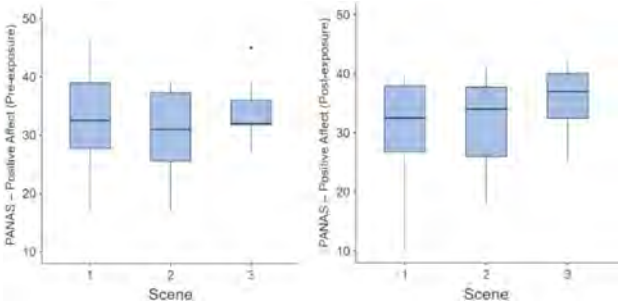


Fig. 3. Boxplots of pre- and post-exposure PANAS Positive Affect scores by scene. Scene 1 represents low vegetation density, Scene 2 medium vegetation density, and Scene 3 high vegetation density. Boxes indicate interquartile ranges, horizontal lines represent medians, and whiskers indicate score dispersion.

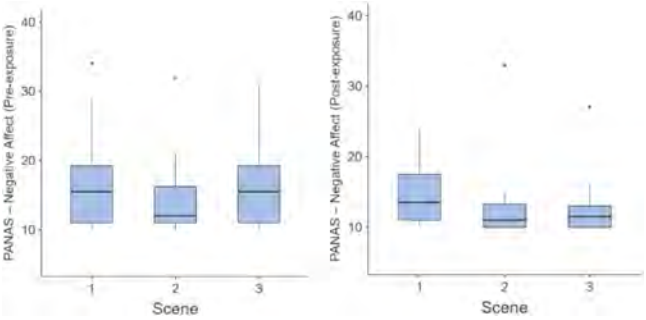


Fig. 4. Boxplots of pre and post exposure PANAS Negative Affect scores by scene. Scene 1 represents low vegetation density, Scene 2 medium vegetation density, and Scene 3 high vegetation density. Boxes indicate interquartile ranges, horizontal lines represent medians, and whiskers indicate score dispersion.

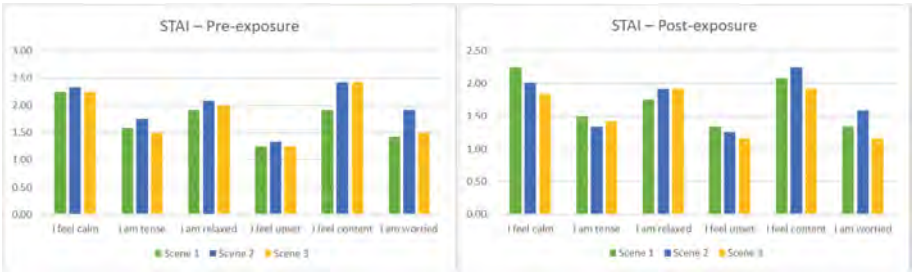


Fig. 5. Bar charts of mean STAI-S item scores before and after exposure, illustrating changes in specific emotional states associated with anxiety.

The results related to positive affect assessed by the PANAS indicate an overall increase in scores in the post exposure period compared to pre-exposure, especially for

emotions related to energy, motivation, and engagement, such as determined, enthusiastic, strong, and inspired. Regarding negative affect, the graphs generally indicate a reduction in scores in the post-exposure period compared to pre-exposure, suggesting a decrease in negative emotional states following the visualization of the scenes. Visually, scenes 2 and 3 show more consistent reductions across several items, such as distressed, upset, nervous and afraid, whereas scene 1 exhibit modest changes (Fig. 6).

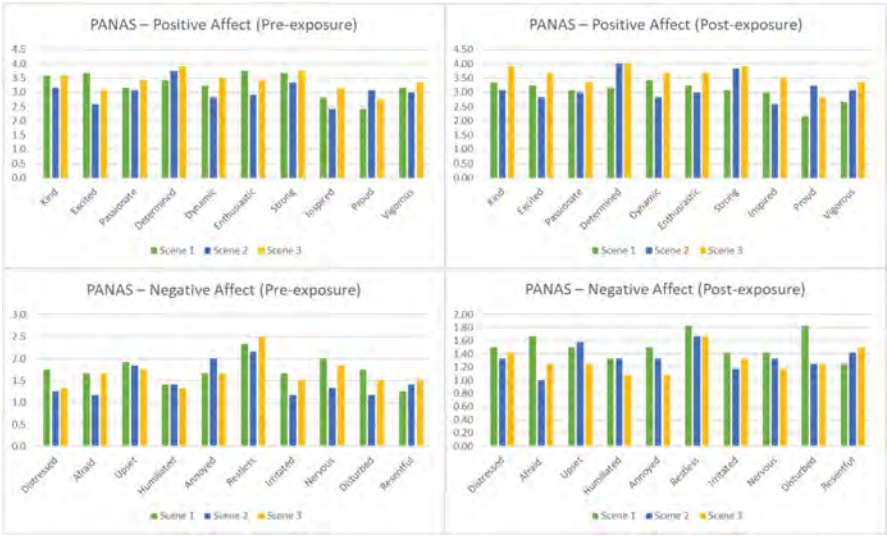


Fig. 6. Bar charts of mean PANAS Positive and Negative Affect item scores before and after exposure, illustrating changes in specific emotional states associated with affective responses.

4 Conclusion

This research is a pilot study that aimed to evaluate the impact of urban scenes with different levels of vegetation on stress and affective responses among Brazilian women. The findings show scenes with medium and high vegetation density showed decreases in anxiety levels when compared to a typically urban scene with low vegetation levels. Furthermore, the results show a statistically significant increase in positive affect in the group of women who viewed the scene with the highest vegetation density, represented by the urban park. These findings indicate the importance of urban green spaces, not only for the discussion of the resilience and sustainability of cities, but also for the health of the people who are part of them. The contemporary city should be one that integrates biotic and abiotic factors in a holistic relationship, aiming for the efficiency of the entire ecosystem. Study limits include difficulty in recruiting volunteers due to some women's apprehension about using virtual reality glasses, lack of interest and limited time available for participation in the research.

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Challenge-Based Circular Learning: Building Awareness, Equity, and Skills for a Circular Built Environment

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Abstract. The transition toward circular cities requires not only technological innovation but also new forms of knowledge production and professional competencies. In this context, architectural education plays a critical role in preparing future designers to address complex socio-technical challenges associated with circular urban systems. This study introduces Challenge-Based Circular Learning (CBCL) as a pedagogical framework that integrates circular economy principles, digital technologies, and real-world urban challenges into architectural design education. The framework was implemented within a master-level design studio conducted in collaboration with local municipality. The studio was structured around three learning phases: raising circular awareness, exploring circular urban systems through digital tools and data-driven approaches, and developing design interventions addressing local urban challenges. Six design projects explored themes such as circular food systems, urban mining, repair economies, and digital platforms supporting circular services. The findings indicate that challenge-based studio environments can foster systems thinking, digital competencies, and community-oriented design approaches while increasing circular awareness. The study highlights the potential of architectural design studios as experimental learning environments supporting the circular transition of the built environment.

Keywords: Architectural Design Studio · Architecture Education · Challenge-based Learning · Circular City · Circular Economy

1 Introduction

Within the built environment, circular economy [1] strategies have increasingly been discussed in relation to construction materials, energy systems, and urban infrastructures. Recent literature [2–4] emphasizes that circular transitions involve social, cultural, technological and institutional transformations. Concepts such as the "circular society" [2] highlight the importance of integrating social practices, governance structures, and collective behavioral change into circular economy strategies. From this perspective, circularity cannot be understood only through technological innovation or industrial processes; it also requires new forms of knowledge production, collaboration, and capacity building across multiple disciplines. Consequently, architectural

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education must evolve to equip future professionals with the competencies required to address these emerging challenges. Traditional design studios, which often focus primarily on organizational, functional and/or formal aspects of design, may not fully address the complex socio-technical dynamics of circular urban systems. Instead, there is a growing need for educational approaches that combine systems thinking [5], interdisciplinary collaboration, and real-world urban challenges. Challenge-based learning [6] has gained attention as a pedagogical approach capable of addressing complex sustainability problems. In challenge-based learning environments, students engage with real-world issues and develop solutions through research, experimentation, and collaborative design processes. This approach encourages students to connect theoretical knowledge with practical problem-solving while interacting with stakeholders and urban contexts.

This study introduces Challenge-Based Circular Learning (CBCL) as a pedagogical approach for integrating circular economy principles, digital technologies and data-driven methods into architectural design education. The aim of this paper is to examine how CBCL can contribute to raise awareness, and professional skills necessary for the circular transition of the built environment.

2 Methodology: Challenge-Based Circular Learning Framework

This study adopts a pedagogical case study approach to investigate how circular economy principles can be integrated into architectural design education through challenge-based learning. The proposed framework, referred to as CBCL, combines circular economy awareness, digital technologies, and collaborative urban problem solving in the design studio environment. The methodology is structured around the implementation of CBCL within a master-level Digital Architectural Design Studio conducted at X University. The studio focused on circularity in urban environments and explored how digital tools and computational methods can support circular economy applications in cities.

Within the CBCL framework, the design studio is positioned as an experimental learning environment where students explore circular urban challenges and develop digital and spatial strategies to address them. The framework integrates theoretical knowledge on circular economy, digital tools for urban systems, and collaborative project development. The studio was conducted in collaboration with the local municipality in Istanbul, providing a real-world urban context for the projects. Students were encouraged to investigate urban conditions, analyze existing circular initiatives, and identify opportunities for circular innovation within the district. This collaboration allowed the studio to function as a form of urban experimentation, where design proposals could address practical challenges related to circular urban transition. By working with real urban contexts and stakeholders, students were able to connect theoretical knowledge with applied design thinking. The structure of the studio was supported by a series of lectures, seminars, reflection exercises, and project presentations distributed throughout the semester. Early weeks of the course focused on introducing circular economy concepts and urban sustainability frameworks, while later stages concentrated on design development and project critiques. The syllabus also included readings on circular cities, digital technologies for circular systems, and emerging practices in sustainable urban

design. Through this structured progression, students were able to gradually move from conceptual learning toward the development of concrete design proposals addressing circular challenges in the urban environment. Figure 1 illustrates the CBCL framework implemented in the design studio.

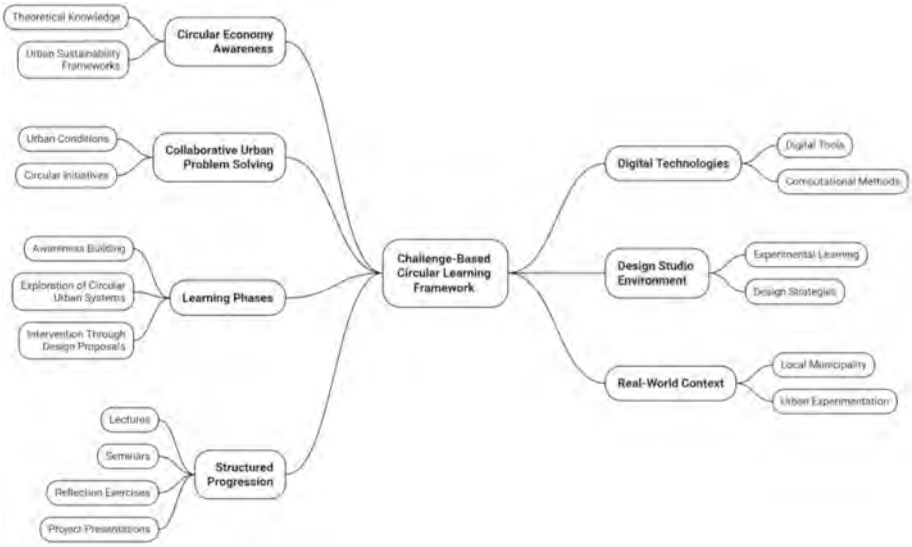


Fig. 1. CBCL Framework (developed by authors).

The methodology is structured around three interconnected learning phases: (1) raise awareness (2) exploration of circular urban systems, and (3) intervention through design proposals. These phases reflect the progression from conceptual understanding to applied design strategies within the studio environment (Fig. 2). The first phase of the CBCL framework focuses on raising awareness and conceptual understanding of circular economy principles in urban contexts. During the initial weeks of the studio, students are introduced to key theoretical concepts related to circular economy, circular cities, and sustainable urban systems. Readings and seminars provide a conceptual foundation for understanding how circular principles can transform the built environment. Reflection exercises and discussions encourage students to critically engage with the social, environmental, and economic implications of circular transitions in cities. This phase aims to develop an initial level of circular literacy and to establish a shared conceptual framework for the studio.

The second phase emphasizes exploration of circular urban systems and enabling technologies. In this stage, students investigate how digital technologies and computational methods can support circular economy strategies in cities. Topics explored in the studio include data-driven decision systems, urban resource flows, digital platforms for circular services, and emerging technologies such as Internet of Things (IoT) systems and geospatial data infrastructures. Students analyze examples of circular city initiatives and

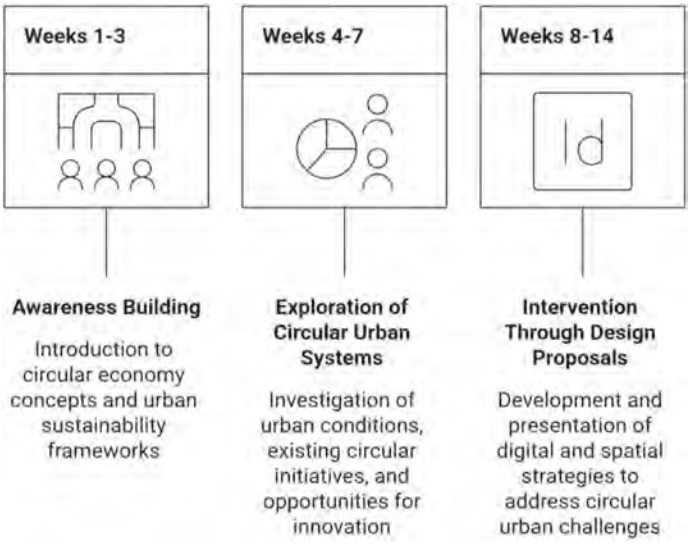


Fig. 2. Methodology of the studio structure (developed by authors).

examine how digital technologies can facilitate resource transparency, material tracking, and new forms of urban service design. Through this process, students develop systems thinking skills and gain familiarity with digital tools that support circular urban transformation. The final phase of the CBCL framework involves intervention through collaborative design projects. Students work in groups to identify circular challenges within the Kadıköy district of Istanbul and develop design proposals that address these challenges through digital and spatial strategies. The projects explore a variety of circular themes, including urban resource management, community-based circular services, circular food systems, repair and sharing economies, and urban material cycles. Throughout this phase, students participate in studio critiques, discussions, and jury evaluations, which support iterative learning and collective feedback. The design studio environment enables students to test ideas, refine strategies, and communicate their proposals through visual and digital representations.

3 Results

3.1 Digital Architectural Design Studio Projects

The studio was offered as a graduate-level course focusing on the integration of circular economy principles and digital technologies within urban design processes. The studio was organized around the urban context of Kadıköy, a district of Istanbul characterized by diverse social, cultural, and economic activities. Through collaboration with Kadıköy Municipality, students were encouraged to analyze local urban challenges and identify opportunities for circular interventions. This real-world context allowed the studio to function as an experimental learning environment where students could explore circular strategies in relation to actual urban conditions.

The course structure followed the three phases described in the CBCL framework: raise awareness, exploration of circular urban systems, and design intervention. During the early weeks of the semester, students were introduced to circular economy concepts and circular city frameworks through readings, lectures, and reflection exercises. In the second phase, students investigated the role of digital technologies in enabling circular urban systems, including data-driven platforms, urban resource mapping, and digital infrastructures for circular services. In the final phase of the studio, students worked in groups to develop design proposals addressing circular challenges in Kadıköy.

Six student projects were developed within the studio, each addressing a different dimension of circular urban systems. Although the projects varied in scale and theme, they all explored the intersection between circular economy principles, digital technologies, and urban design strategies. The Circular Bazaar (1) project investigated how local markets could function as circular infrastructures that support repair, reuse, and community exchange. The proposal introduced a digital platform connecting vendors, repair services, and residents, enabling circular consumption practices and strengthening local economic networks. The Circular Food Systems (2) project focused on urban food waste and distribution networks. The design proposed a digital platform connecting restaurants, markets, and food-sharing initiatives in order to facilitate the redistribution of surplus food and reduce waste within the district. The Urban Mining Platform (3) project addressed construction and demolition waste by proposing a digital system that enables the tracking and exchange of reusable building materials. The project explored how urban mining strategies could support circular construction practices and material reuse in cities. The Earthquake Accessibility (5) project focused on resilience and accessibility within urban environments. The proposal integrated geospatial data and digital infrastructures to improve emergency mobility and access to resources in post-disaster scenarios. The Circular Stadium (6) project examined how large-scale urban infrastructures could incorporate circular energy systems, material reuse strategies, and sensor-based monitoring technologies. The design explored how digital tools can support circular management of large urban facilities. The Craft and Repair Economy [6] project focused on strengthening local craft networks and repair practices through digital platforms connecting artisans, workshops, and local communities. The proposal aimed to promote circular consumption by extending product lifecycles and supporting knowledge exchange within the neighborhood. Students are engaged with issues such as systems thinking, community participation, circular service design, material lifecycle analysis, and digital platform development.

3.2 Circular Skills and Learning Outcomes

Beyond the individual design proposals, the studio process enabled the development of a range of competencies related to circular urban systems and sustainable design practices. Within the CBCL framework, the design studio functioned not only as a platform for generating spatial and digital solutions, but also as a learning environment where students developed new forms of awareness, knowledge, and professional skills relevant to circular transitions in the built environment. In addition to project-based learning, the development of circular competencies was supported through various studio activities, including seminars, readings, group discussions, critiques, and jury presentations.

These pedagogical components played a key role in fostering circular awareness and collaborative learning within the studio environment. Table 1 summarizes how different learning activities contributed to the development of specific competencies related to circular urban transitions.

Table 1. Learning Activities and Circular Skills Development.

Learning activity	Purpose in the studio	Skills developed
Seminars & lectures	Introduction to circular economy and circular cities	Circular awareness, theoretical literacy
Assigned readings	Understanding circular economy frameworks and urban sustainability	Critical thinking, conceptual understanding
Group discussions	Reflecting on circular challenges and urban case studies	Collaborative learning, argumentation
Studio critiques	Iterative feedback on project ideas	Design reasoning, problem framing
Interim reviews	Evaluation of project progress	Analytical thinking, communication
Jury presentations	Presentation of design proposals to instructors and external reviewers	Professional communication, visual storytelling

One of the most significant outcomes of the studio was the development of systems thinking. Circular economy challenges require understanding complex relationships between material flows, infrastructures, communities, and urban services. Through the analysis of urban conditions in Kadıköy and the development of project proposals, students were encouraged to examine how different urban systems interact with one another. For example, projects focusing on food systems and urban mining required students to analyze resource cycles, supply chains, and material lifecycles within the city. This process helped students move beyond isolated design interventions and instead consider the broader urban systems that shape circular practices Another important learning outcome involved the development of digital and data-oriented design competencies. Many of the proposed projects incorporated digital platforms, data infrastructures, or smart technologies aimed at supporting circular services. Through these explorations, students engaged with digital tools as mediators of circular practices in cities. Rather than focusing exclusively on physical architectural interventions, the projects explored how digital systems—such as mobile platforms, geospatial data applications, and digital marketplaces—can facilitate circular interactions between urban actors.

The studio also contributed to the development of community-oriented design thinking. Several projects addressed social dimensions of circularity by proposing systems that support collaboration between local actors, such as artisans, market vendors, or neighborhood communities. These proposals emphasized the role of social networks and collective participation in enabling circular practices. As a result, students were

exposed to the social and cultural dimensions of circular economy, including issues related to community engagement, local knowledge exchange, and equitable access to urban resources. In addition to these thematic competencies, the studio environment encouraged collaborative and interdisciplinary learning. Students worked in groups and engaged in iterative discussions, critiques, and project reviews throughout the semester. The challenge-based format required students to combine architectural design skills with knowledge from other fields, including urban studies, digital technologies, and sustainability research. This interdisciplinary approach supported the development of problem-solving skills and the ability to navigate complex urban challenges.

Finally, the studio contributed to raising circular awareness among students. Through readings, discussions, and project-based explorations, participants developed a deeper understanding of how circular economy principles can influence urban design practices. The combination of theoretical knowledge and applied design experimentation allowed students to translate abstract sustainability concepts into tangible urban strategies. In this sense, the design studio functioned as a learning environment where awareness of circular challenges could evolve into actionable design thinking. Table 2 presents the competencies developed through the student projects.

Table 2. Circular Competencies Developed Through Studio Projects.

Project	Circular challenge	Skills developed
Circular Bazaar	Local circular economy	Community engagement, service design
Food systems	Urban food waste	Systems thinking, logistics analysis
Urban mining	Construction waste	Lifecycle thinking, material flows
Earthquake accessibility	Urban resilience	GIS analysis, data-driven planning
Circular stadium	Circular infrastructure	Multi-scale systems design
Craft economy	Repair economy	Social innovation, sharing economy

4 Conclusion

As circular economy principles increasingly shape urban sustainability agendas, architectural education must evolve to prepare future designers for the complex challenges associated with circular transitions. This study introduced CBCL as a pedagogical approach that integrates circular economy concepts, digital tools, and real-world urban challenges within an architectural design studio. Implemented in the Digital Architectural Design Studio at X University, the CBCL framework enabled students to explore circular urban systems through collaborative projects developed in the context of Kadıköy, Istanbul. The findings demonstrate that design studios can function as experimental learning environments where circular awareness, systems thinking, and digital competencies can be developed simultaneously. Through a combination of seminars, readings, group discussions, critiques, and project-based learning, students engaged with circular economy principles not only at a conceptual level but also through applied design strategies

addressing urban challenges. The results indicate that CBCL can contribute to the development of key competencies required for circular urban transitions, including systems thinking, community-oriented design, digital platform development, and collaborative problem solving. By linking theoretical knowledge with real-world experimentation, the design studio provided a framework for translating circular economy concepts into practical urban strategies. The study suggests that architectural design studios have the potential to act as educational platforms for fostering circular awareness and capacity building within the built environment. Future research may further explore how similar pedagogical models can be applied in different urban contexts and educational settings to support broader transitions toward circular and sustainable cities.

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On-the-Job Training for Sustainable Requalification of Buildings

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Abstract. The transition to sustainability in the building sector urgently requires updating operational skills and knowledge of lightweight, reusable, and recyclable materials, as well as low-impact construction techniques. This contribution presents some results of the research project Co-WIN which, in the process of returning buildings confiscated from organized-crime to the community, provides social benefits to various stakeholders and vulnerable people, by activating an on-the-job training model based on "construction-site-schools" during the building refurbishment works. The "construction site schools" can be an effective lever both for raising the level of operators' professional competence, and for promoting the adoption of innovative and sustainable construction techniques, characterized by ease of assembly, cost-effectiveness, recyclability and reusability. Furthermore, the use of Massive Open Online Courses makes it possible to transfer this "on-the-job" training to the university students, both to share construction-site knowledge and to create a "culture of sustainability" based on the concrete choice of sustainable solutions. The application of these replicable training models acts as a catalyst for spreading awareness and skills among operators and future designers increasing their capacity to support sustainable transitions. The paper presents the results of the "Co-WIN construction-site school" case study illustrating the assessment (based on a comparative analysis of training hours, life cycle costs and qualitative sustainability criteria) for choosing lightweight and disassemblable construction technologies, the dissemination of knowledge and learning in architectural education based on a Massive Open Online Course.

Keywords: Construction-site school · Lightweight technology · Digital training · On-the-job training · Construction education

1 Sustainable Transition and New Job Opportunities

The goal of reducing climate-changing gas emissions and limiting energy consumption in the construction sector has brought urgent attention to the issue of regenerating the built environment, particularly through the renovation of existing buildings, as emphasized by the "Renovation Wave" strategy, promoted by the European Union, which aims to double the annual rate of energy renovation of buildings by 2030 (European Commission, 2020).

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However, building renovation consumes natural resources and generates environmental impacts. It is therefore necessary to embrace the opportunity offered by building regeneration to promote sustainable construction solutions designed for dismantling, capable of promoting resource circularity strategies in line with circular economy policy requirements. In addition to environmental objectives, the Renovation Wave strategy also aims to achieve social benefits through job creation and creating partnerships between local authorities, social housing providers, and SMEs.

Renovations are labour-intensive activities and therefore that local construction companies will have a very strong need to find labour in the face of rapidly growing demand for work (ANCE, 2024).

Furthermore, the need to renovate using techniques that comply with environmental sustainability and circularity requirements also requires training for construction workers, who are called upon to abandon traditional construction solutions characterized by the use of massive and inflexible techniques in favour of innovative construction solutions that reflect the requirements of lightweight, reusable, and recyclable materials, as well as low-impact construction techniques.

Trainees (students in the construction field, or vulnerable individuals seeking social rehabilitation through employment – e.g., NEETs, refugees, and migrants) can become key actors in this transformation, as they can be trained and acquire new skills that are useful for carrying out circular and sustainable demolition and construction operations.

Specialized training in the field of circular and sustainable building renovation can expand job opportunities and promote social and economic inclusion for vulnerable people (Cantillon and Van Lancker 2013; Segers et al. 2023).

Renovation interventions on confiscated buildings have been identified as a particularly significant field of application, as they can act as catalysts for the Societal and Educational dimensions, promoting the development of new skills and capacity-building processes that are essential for guiding the sustainable transitions, while at the same time raising awareness among stakeholders and people in general.

Confiscated building stock represents a largely unutilized collective resource in need of renovation, which has intrinsic material, social, and symbolic value. In Italy, the total number of confiscated buildings from organized crime is 43,422, predominantly apartments in condominiums and small housing units (ANBSC, 2024). The presence of confiscated properties in need of renovation and reuse is becoming an increasingly widespread issue across Europe (e.g., EU Directive 2024/1260) and at the global level. The confiscated building stock is of particular interest as it directly involves public administrations which have the strategic leverage to act as promoters of sustainable environmental and social dynamics.

This paper presents some results of the Co-WIN research project, funded by the "Polisocial Awards 2021", which, through the renovation process of confiscated buildings, implements "on-the-job" training for students and vulnerable people, generating social value and spreading knowledge on innovative construction technology oriented towards circularity (Campioli et al., 2024).

2 The Co-WIN Model

In order to encourage redevelopment initiatives and enhance their social purpose, the Co-WIN research project designed and tested, both theoretically and practically, an innovative management model for the various stages of the renovation process and the return of confiscated properties to the community, with the aim of enhancing their social value through training processes at various levels (Campioli et al., 2024). The Co-WIN model is based on the implementation of "construction site-schools train" for social integration, educational and technological experimentation through multistakeholder networks based on win–win logic (Giorgi et al., 2025). The structured and proactive system of relationships acts as a catalyst for virtuous win–win processes across multiple occasions of renovation and reuse of confiscated assets (Nielsen 2009; Eshun et al., 2021).

The Co-WIN project creates a collaborative ecosystem designed to foster synergies that benefit all parties involved in the redevelopment of confiscated assets. Through multidisciplinary "working groups," the research team and project partners have integrated expertise to develop procedural recommendations, addressing regulatory complexities while experimenting with innovative training models.

Through the win-win stakeholder network, the Co-WIN project facilitates "on-the-job" training through the "construction-site schools" (Law 264/1949; Law 418/1975). In line with existing regulations, the construction site-school model applied in the Co-WIN experiment is an opportunity for "on-the-job" training combining theoretical and practical training, involving trainers and trainees on a real construction site.

The Co-WIN construction-site schools trains both vulnerable people who involved in building renovation activities, and university students in the field of construction who collaborate with designers and public administrations throughout the design and management processes of building renovation projects.

The training framework of the construction-site school includes training institutions, which provide specialized instruction on both traditional and innovative construction techniques, and manufacturers of building components, who offer on-site training for specific innovative technologies aligned with sustainability and circularity requirements. The Co-WIN construction-site school applies tailor-made training models specific to the context and social categories involved (students and vulnerable people). These training models address the ongoing need for professional development driven by the evolution of building performance and environmental standards within the framework of circular economy objectives.

2.1 Definition of Criteria for Choosing Sustainable Construction Solutions

To guide the renovation of confiscated buildings towards sustainable solutions, the Co-WIN project has defined a framework of objective and measurable evaluation criteria, used to evaluate different construction techniques. Below are the analysis criteria and the sources from which to obtain information (Table 1).

Therefore, within the Co-WIN training sites, the choice of products used for building renovation is based on a comparative analysis of training hours, life cycle costs, and qualitative sustainability criteria for each proposed solution adopted. This approach leads

to choices that are optimized as possible for the learning environment and sustainability requirements.

Table 1. Criteria for choosing construction solution for confiscated building renovation process and their corresponding data sources

Criteria		Source
Training hours required to learn how to carry out the work		Training programs provided by training institutions
Life cycle costs of the building work (material price and end-of-life management costs)		Regional Price List for Public Works
Labor costs (for assembly and disassembly/demolition)		Regional Price List for Public Works
Qualitative sustainability criteria	Lightweight	Technical data sheets for building products and designers/builders' know-how
	Disassembly	
	Reusability	
	Recyclability	

The data used for the analysis of training hours is available in the training programs offered by training institutions (number of training hours).

The data used for the life cycle cost analysis comes from the Regional Price List for Public Works, an official and comprehensive catalog published annually by the Lombardy Region. It establishes the standard and regulated unit costs for construction materials, labor, machinery and works (costs/unit).

The data used for the qualitative sustainability analysis comes from the technical data sheets of construction products and the expertise of designers and builders in the field of construction solutions.

2.2 Definition of Modality to Share Knowledge and Construction Site Experience in Architectural Education

To ensure that a large number of university students in the field of construction have access to the activities and dynamics of construction sites, the construction site-school experience is reproduced in a digital learning environment. This approach enables the transfer of crucial skills related to procurement procedures and site management, as well as technical and practical construction insights into specific sustainable solutions for the redevelopment of buildings.

Following an analysis of pedagogical frameworks suitable for transferring the construction site-school experience into university teaching, a Massive Open Online Course (MOOC), delivered through the "Polimi Open Knowledge" (POK) platform of the Politecnico di Milano, was designed and developed. This virtual learning environment was developed with the support of the collaboration and specialist support of METID (Innovative Methods and Technologies for Teaching) at the Politecnico di Milano, which allowed the teaching content to be disseminated with scientific rigor through innovative

methodologies and technologies, transforming the physical experience into a digital path. The course includes video recordings produced during the "construction site-school" for the renovation of confiscated buildings (Pilot Project).

3 Results and Discussion

3.1 Sustainable Construction Technologies Selection

In the context of the project for the renovation and reuse of confiscated buildings within the CO-WIN model, the choice of construction solutions not only involves compliance with regulatory requirements and economic advantage, but also environmental sustainability requirements, which can be pursued throughout the building life cycle, and characteristics suitable for "on-the-job training", ensuring overall work quality of the work.

The "Co-WIN construction site-school" Pilot Project represents a practical application of on-the-job training for the sustainable renovation of buildings. In this context, the criteria for choosing sustainable construction solutions were applied during the interior design process. The Pilot Project required a new internal layout, involving the construction of vertical partition walls and the reconfiguration of part of the electrical system. The design options under consideration include both massive and lightweight partitions. The comparative analysis was conducted to identify the optimal solution in terms of costs, trainees' ease of learning during installation, and life-cycle sustainability. Although this case study represents a relatively simple case, it demonstrates that the same comparative analysis could be applicable and replicable to other alternative construction solutions.

In this Pilot Project case study lightweight, dry, and easily removable construction solutions were preferred over traditional ones, after comparing the hours required for operational skills training, the life cycle costs of the construction solutions and the qualitative sustainability criteria.

The example of the comparative analysis carried out to compare two different construction choices (traditional brick partition wall VS plasterboard partition wall) and define the construction technology suitable for the construction-site school activities is reported in Table 2. The data sources used for the comparative analysis are those reported in Table 1 (column: "Source"). The total life cycle costs include installation and future demolition of vertical partition per square meter, dividing the costs into materials costs, labor costs, other costs (such as the necessary temporary works).

The comparative analysis shows that a drywall solution requires less labour than the traditional solution, resulting in lower overall costs. This is because the lightweight option is easy to use and quick to install, which provides economic benefits. In addition, the lightweight solution allows for easy handling and simultaneous collaboration between a small number of operators. These features also facilitate skill acquisition, requiring fewer training hours. The analysis shows that, based on estimates from training institutions, learning traditional brick masonry laying requires a longer training path due to mortar management and the manual skills needed to ensure structural stability.

The dry solution also offers advantages in terms of environmental sustainability. The ease of integration of the systems avoids complex installations and the generation of micro-demolitions and waste, offering advantages during the use phase in terms of

Table 2. Comparative analysis to choose construction solution based on the defined criteria

Bricks	Criteria	Plasterboard
↑ 37,68 €/m²	labor costs	21,32 €/m² ↓
↓ 24,89 €/m²	material costs	26,39 €/m² ↑
↑ 18,94 €/m²	other costs*	12,90 €/m² ↓
↑ **81,51 €/m²**	**Total Life Cycle costs**	**60,61 €/m²** ↓
Basic training: 40-80 hours Advanced training: 150+	Training hours	Basic training: 16-24 hours Advanced training: 40-60
⊖	Lightweight	✓
⊖	Disassembly	** ✓ ⊖
⊖	Reusability	*** ✓ ⊖
✓	Recyclability	✓

* Other costs is included in the regional construction price list
** Potential for disassembly through careful deconstruction.
*** High reusability potential, if components are properly disassembled.

*Other costs is included in the regional construction price list, **Potential for disassembly through careful deconstruction, ***High reusability potential, if components are properly disassembled.

inspect ability, maintenance, and replacement of individual parts, extending the useful life of the building. Furthermore, the dry solution has the potential to be disassemble, promoting flexibility in interior spaces in response to usage needs over time. This also facilitates the potential reuse or recycling of products at the end of their life cycle, in line with the objectives of the circular economy.

It is important to emphasize that this comparison must be conducted on the basis of equivalent performance, especially when the design alternatives comply with minimum regulatory standards (e.g., thermal transmittance, acoustic resistance, etc.). For instance, in this case study, acoustic performance was established as a baseline requirement shared by both design options.

Furthermore, it is relevant to highlight that "qualitative" environmental criteria would not be sufficient to evaluate environmentally sustainable aspects. A comparison of actual environmental sustainability would require the application of "quantitative" methods, such as Life Cycle Assessment, to measure environmental impacts through precise metrics (e.g., kgCO2eq).

3.2 Dissemination of Knowledge and Experiential Learning in Architectural Education

The MOOC course aims to offer the experience of an "educational visit to construction sites", which has long been considered an important activity in architecture and engineering programs, as an effective mode of learning.

The aim is to support the understanding and reinforcement of concepts, and to increase awareness of construction practices and technical and economic constraints, with a particular focus on sustainability and Life Cycle Thinking.

The course, which is delivered online and free of charge, is classified as "073 –Architecture and Construction" in section "K - Knowledge," according to the "European Skills, Competences, Qualifications and Occupations (ESCO)", i.e., the standard classification that identifies and categorizes the skills, competences, qualifications and occupations relevant to the labor market and education in Europe (European Commission, 2025). The course is divided into three "weeks" (consisting of multiple lessons in text and video format), through which students will acquire: i) the ability to identify the complex factors that characterize the renovation processes of public buildings; ii) an understanding of the operators involved in the construction process, the relationships between them, and their responsibilities in the project; iii) an understanding of the effects of construction technique choices; iv) an understanding of the importance of installation quality in construction solutions and the impact of worker training on successful implementation. In particular, the focus on the design and construction phases highlights the advantages of choosing construction solutions characterized by lightweight design, speed of assembly/disassembly, reusability and recyclability, as well as the regulatory aspects of the quality control process for the execution of work to the highest standards.

The MOOC represents a path of 'inclusiveness' as it gives all students access to experience and knowledge. Moreover, the course is open and could also be used by public authorities, which would like to learn more about the relevant legislation the win-win model for implementing training through the "construction site-school" approach.

4 Conclusion

This paper presents selected results of the Co-WIN research project showing how the redevelopment of properties confiscated from organized crime can become a powerful catalyst for social value and technical innovation through the construction site-school model. On-the-job training experiences for vulnerable people and university students enable the dissemination of operational skills that are crucial for the transition to sustainable and circular construction and promote social inclusion and legality. The results demonstrate the application of evaluation criteria for the choice of construction technologies. Specifically, in the case study analyzed, lightweight, dry, and demountable partition solutions (instead of traditional masonry) can facilitate rapid learning for workers and ensure economic benefits throughout the building life cycle, while also meeting environmental sustainability criteria.

Extending the physical experience of the construction site-school into a digital learning experience, through the development of Massive Open Online Courses (MOOCs), ensures widespread dissemination of knowledge, training a new generation of designers and operators equipped with knowledge of sustainability and circular economy strategies.

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Circular Cities and Communities: Tools, Methods and Principles of Circular Built Environment Education

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Abstract. The transition toward a circular built environment requires more than technological optimisation; it implies a reconfiguration of how value is produced, coordinated and spatialised across material, institutional and territorial systems. Within this context, circularity challenges conventional approaches within built environment education, which often address sustainability as a technical add-on rather than as a structuring principle. Built environment education faces growing pressure to prepare professionals capable of addressing the systemic transformations required for circular transition. This raises a central pedagogical challenge: how can built environment education move beyond technical sustainability modules and instead structure learning around the systemic logics of circularity? Circularity functions as a transversal theme connecting ecological, social, institutional and spatial dimensions through an expanded understanding of value creation and coordination within the built environment. This paper argues that circularity should operate as an organising principle within built environment education rather than as a thematic module or technical design task. The paper presents the pedagogical model implemented within the Circular Cities & Communities (CC&C) programme at Zuyd University of Applied Sciences in the Netherlands. The programme is structured around three educational lines of Flow, Process and Design, which respectively address material and resource circulation, governance and stakeholder coordination, and spatial interventions. Embedded within urban living labs, the programme connects education with governance processes, infrastructural systems and construction practices. The paper analyses the conceptual foundations of this model and reflects on insights from its first year of implementation, highlighting strengths, challenges and transferable lessons for circular built environment education.

Keywords: Circular Design · Circular Flow · Circular Process · Circular Transition · Built Environment Education

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1 Introduction

More than a decade after the formalisation of the circular economy in Europe and several years after the European Green Deal and Circular Economy Action Plan, the transition toward a circular built environment appears to require structural reconfiguration of the construction sector rather than isolated technological optimisation (European Commission, 2015, 2020). While circular design and construction discourse often focuses on material efficiency, lifecycle assessment and waste reduction, sustainability transitions scholarship frames circularity as a broader socio-technical shift in how value is defined, coordinated and spatialised within the built environment (Markard et al., 2012).

Built environment education, however, frequently remains fragmented across disciplines, scales and professional roles, thus leading to circularity being addressed as a technical module rather than as a structuring principle by design disciplines and construction curricula. Recent debates in architectural education similarly call for pedagogical rethinking under climate uncertainty, beyond technological optimisation alone (Ioannou, 2023). These arguments resonate with the broader sustainability transitions literature, which frames transformations as long-term, multi-actor and multi-scalar processes rather than linear technical upgrades (Markard et al., 2012).

This paper argues that circularity must function as a primary organising principle within education itself. Rather than an "add-on" topic or technical design task, circularity should structure how students analyse flows, understand governance processes and execute design interventions. The objective of this paper is therefore to introduce, conceptualise and evaluate the pedagogical model for circular built environment education applied at the Circular Cities & Communities (CC&C) bachelor programme within the Built Environment Academy of Zuyd University of Applied Sciences,[1] and to reflect on its first year of implementation.

The contribution is threefold. First, the paper clarifies circularity beyond material loops by engaging definitional debates within circular economy scholarship. Second, it positions the Flow–Process–Design pedagogical model within sustainability transitions theory. Third, it analyses early implementation insights from the overarching infrastructure of the urban living labs, thus identifying strengths, tensions and transferable lessons.

2 Circularity as an Organising Principle

Circular economy scholarship demonstrates substantial conceptual ambiguity. Analyses of circular economy definitions reveal more than one hundred distinct interpretations, ranging from resource efficiency to systemic societal transformation (Kirchherr et al., 2017). This definitional plurality complicates operationalisation in research, policy and

[1] The programme developed by Smart Urban Redesign (SURD) research centre responds to the need for built environment graduates able to combine technical literacy, systemic reasoning, collaborative capacity and design agency across material, institutional and spatial domains. This need stems from the gap between built environment education and emerging professional practices.

education (Geisendorf & Pietrulla, 2018). Some framings emphasise technological optimisation, while others articulate circularity as a broader sustainability paradigm shift (Geissdoerfer et al., 2017).

Recent scholarship advances the notion of a circular society, emphasising that circularity entails reconfiguration of social, institutional and value systems beyond resource efficiency alone (Calisto Friant et al., 2024). From a sustainability transitions perspective, such paradigm shifts involve reconfiguration of established socio-technical regimes rather than incremental technological substitution (Markard et al., 2012). Regimes, comprising rules, infrastructures, institutional routines and professional norms, are strong representatives of linear production-consumption patterns. For this reason, a coordinated transformation across material systems, governance arrangements and spatial practices is required to reach the circular transition.

Circular economy ecosystems literature highlights the role of coordinated actor constellations as a crucial element in generating sustainable system-level outcomes (Aarikka-Stenroos et al., 2021). Similarly, in the built environment, complex systems analyses demonstrate that circular strategies operate through interdependencies, feedback loops and multi-actor coordination (Rios et al., 2022).

In response to this complexity, this paper defines circularity through three interdependent aspects: Flow, Process and Design. These are epistemic lenses that reorganise how value is understood and produced: 1. Flow conceptualises value as circulation; 2. Process conceptualises value as coordination; and 3. Design conceptualises value as a spatial operator (Iacovidou et al., 2021; Leclercq & Smit, 2023). Together, these aspects provide a systemic scaffold that mirrors the interdisciplinary and trans-scalar character of socio-technical transitions. Circular value cannot be realised through optimisation of flows alone, nor through governance reform or spatial innovation in isolation. Their interdependence reflects regime-level transformation dynamics identified in transition research (Markard et al., 2012), as well as the uncertainty that derives from such processes (Ioannou et al., 2022). Positioning circularity as an organising principle therefore requires a reorganisation of educational knowledge structures, curricula, assignments, assessment criteria and competences, so that they reflect the systemic interdependencies required for circular transition.

3 The Flow–Process–Design Pedagogical Model

The CC&C programme structures circular education through the three aspects of Flow, Process and Design as mutually conditioning competencies across spatial scales.

3.1 Flow

The Flow aspect focuses mainly on understanding circularity through values as circulation, therefore highlighting movement of materials, energy, people and information within the built environment. However, flows are not merely technical systems to be optimised. They are embedded within existing organisational routines, procurement structures and construction practices. Altering one material or energy flow often has implications for contracts, responsibilities and long-term maintenance strategies. Flow

education therefore extends beyond efficiency calculations; it trains students to recognise interdependencies and anticipate practical consequences of circular interventions within real building and urban contexts. Students conduct flow mapping and analysis and life cycle assessment. Systematic reviews in circular construction research demonstrate the importance of integrating lifecycle and material recovery strategies (Akhimien et al., 2021; Osobajo et al., 2022).

3.2 Process

The Process aspect highlights the coordination value of circularity, thus addresses governance, procurement, financing and stakeholder coordination and management. As circular design and construction depend on collaboration between municipalities, contractors, developers and communities, systemic design scholarship emphasises engagement with interrelated actors in complex societal contexts (Bijl-Brouwer & Malcolm, 2020). Students conduct stakeholder mapping, role-play simulations and governance scenario development, while incorporating transition management strategies and developing business cases. Through this lens, circularity becomes an institutional coordination challenge aligned with regime transformation dynamics.

3.3 Design

The Design aspect integrates flow analysis and process negotiation into spatial interventions, thus operating as mediating practice where physical settings can influence socio-spatial practices and behaviour. Studios emphasise emergent approaches that support adaptability, design-for-disassembly, scenario-based transformation, thus revealing the necessity to rethink how to design with uncertainty in multi-crisis environments (Andaloro et al., 2026). Circular cities scholarship further links spatial resilience with systemic reasoning (Chiappini & Abujidi, 2023). Design enables students to translate systemic insights into territorially embedded interventions responsive to material, social and local conditions.

3.4 Integration Across Scales

The pedagogical model operates through a trans-scalar approach, from materials to territories (Ioannou et al., 2022). Early assignments focus on component-level circular strategies, progressing toward neighbourhood and regional interventions. Flow, Process and Design are repeatedly revisited across this progression, creating cumulative learning rather than isolated thematic blocks as educational complexity increases. In this way, circularity becomes deeply embedded in the educational structure itself.

4 Urban Living Labs as Knowledge Ecosystem

The CC&C programme is embedded in Urban Living Labs (ULLs) in Limburg, the Netherlands, which provide an applied setting for linking circular education with regional planning, construction practice and stakeholder engagement. ULL scholarship positions

such labs as innovation infrastructures and platforms for student social learning, knowledge exchange and transdisciplinary experimentation (Blezer et al., 2024; Tercanli & Jongbloed, 2022; van der Wee et al., 2024). Their relevance to higher education lies in connecting teaching, research and regional development, while geographically bounded settings can support co-production and applied learning (Abujidi et al., 2024).

Within this setting, students encounter real planning processes, infrastructural systems and community initiatives. The ULLs offer continuity across cohorts and projects, supporting cumulative knowledge production and stakeholder relationships. Circular strategies are thus explored in relation to existing governance frameworks and construction realities. Through incremental regional embedding, Urban Living Labs provide a context for connecting pedagogical experimentation with construction practice and policy development.

5 Educational Development and Preliminary Insights

Scholarship on sustainability pedagogy emphasises deliberate capability building rather than transmissive teaching (Sandri & Holdsworth, 2022). Earlier work on environmentally conscious design education similarly argues for sustainability as a core curricular value (Domenica Iulo et al., 2013). Within this perspective, the first year of the CC&C programme was developed and reflectively evaluated as an exploratory curriculum implementation.[2]

The first year consists of four ten-week blocks. The first part introduces the built environment through scale-defined learning lines on building, neighbourhood and city, alongside technical skills and professional development. The second part addresses circularity through a collective transition project structured around the Flow–Process–Design aspects, requiring students to connect resource and infrastructural flows, stakeholder coordination and spatial interventions.

Three analytical criteria guided both the development and reflective evaluation of the first-year implementation: 1. Systemic integration, referring to the extent to which student work connected material and infrastructural flows with organisational processes and spatial design decisions; 2. Scalar coherence, referring to the capacity to relate decisions at material and building levels to neighbourhood, urban and territorial implications; and 3. Implementation awareness, referring to the degree to which proposals engaged governance structures, stakeholder constellations, feasibility considerations and construction-related constraints. These criteria helped assess whether circularity began to operate as an organising principle rather than as an isolated theme. In the programme, they materialise through constructive alignment between assessment criteria, educational activities and learning goals.

Three preliminary insights emerged. First, the Flow–Process–Design framework supported emerging systemic reasoning, although unevenly. Student outputs increasingly connected built environment components to infrastructural and policy contexts, especially when assignments required movement across scales. However, students more

[2] This evaluation is exploratory and reflective and draws on the bachelor's curriculum documents, assignment briefs, rubrics, together with student artefacts, written assessments, tutor observations and curriculum-team reflections from the first year of implementation.

easily identified flows, actors and spatial conditions separately than synthesised them into coherent circular transition proposals.

Second, reflection sessions and assessment discussions indicated growing implementation awareness. Stakeholder mapping, business-case development and Urban Living Lab encounters helped students understand circularity as a collaborative process rather than a purely technical design task. Yet integration into the Urban Living Lab ecosystem remained gradual, as students needed more familiarity with the regional context, governance actors, circular transition concepts and local tools for their implementation.

Third, the implementation exposed a tension between circular education and established disciplinary expectations. Interaction with Urban Living Lab stakeholders and interdisciplinary peers was productive, but students often relied on conventional professional roles when interpreting circular transition challenges. This indicates a need to further calibrate assignments, feedback and assessment criteria around systemic coherence, implementation awareness and cross-disciplinary collaboration. These insights are therefore indicative outcomes of an early-stage implementation and form the basis for future exploration of circular competences needed in the built environment.

6 Discussion and Conclusion

The initial insights indicate that circularity may function as an organising principle for built environment education when explicitly structured across Flow, Process and Design aspects (Table 1). Interpreted through sustainability transitions scholarship, the model offers an educational framework through which students can begin to engage with the systemic, multi-actor and multi-scalar character of circular transition in the built environment (Markard et al., 2012), while grounding circularity in clearer conceptual foundations (Geissdoerfer et al., 2017; Calisto Friant et al., 2024). Embedding circularity within an education ecosystem appears to strengthen the potential alignment between design education, construction practice and governance systems. The Urban Living Lab setting provides a promising context for this integration by connecting teaching, research and regional challenges. However, institutional coordination, assessment redesign and sustained stakeholder collaboration remain necessary to consolidate circular competencies across scales.

The transferable contribution of this study lies in articulating a pedagogical structure that may inform comparable circular built environment curricula by integrating circular economy scholarship with systemic design and sustainability transitions perspectives. By operating from materials to territories, the Flow–Process–Design pedagogical model offers a basis for teaching circularity as a trans-scalar and systemic challenge, while future research will develop measurable indicators to test and refine the preliminary insights reported here.

Table 1. Educational translation of circularity within sustainability transitions.

Pedagogical model	Circular economy focus	Transition perspective	Educational activities in CC & C
Flow	Resource circulation, lifecycle loops	Reconfiguration of systems	Flow mapping, material passports, lifecycle scenario modelling
Process	Business models, governance coordination, stakeholder management	Institutional change & actor alignment	Stakeholder mapping, procurement analysis, role-play simulations
Design	Circular building strategies, adaptability	Spatial embedding of systemic change	Research-by-design studios, multi-scalar interventions
Ecosystem		Multi-actor transformation arenas	Urban Living Lab as knowledge ecosystem

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Community-Led Zero Waste Practices in Ecovillage Gatherings: An Observational Study

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Abstract. The global escalation of waste generation and the limits of linear management systems underscore that waste is not merely a technical inconvenience, but a complex socio-environmental challenge. Studies show that addressing this complexity requires not only technological solutions, but also governance arrangements, socio-material practices and learning processes that foster behavioural change, collective responsibility, and community-level forms of circularity. Ecovillages are relevant in this context because they serve as sites of social innovation where holistic, system-based approaches to sustainability are tested at multiple scales. They also organise continent-scale gatherings within the broader movement coordinated by the Global Ecovillage Network, creating environments where waste management practices are embedded in daily routines and shaped by shared responsibilities, informal learning and community-based organisation. This study draws on observational data collected at ecovillage gatherings in Europe and Latin America between 2022 and 2025, offering a translocal perspective on community-led waste management. The methodology includes participant observation, field notes, visual documentation and the review of on-site communication materials and participant guidelines when available. The observations indicate that sorting stations, clear visual guidance, volunteer coordination, and peer learning constitute an integrated socio-environmental system, comprising social and material elements that support waste reduction, reuse and composting. The findings suggest that technological efficiency alone is insufficient and that effective waste management depends on the alignment between appropriate technologies and the social, cultural and organisational structures that enable their use. Ecovillage gatherings function as educational environments that cultivate awareness, skills and collective capacities essential for circular and regenerative transitions.

Keywords: Zero Waste · Waste Management · Community-led initiatives · Participatory Learning · Collective Action

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1 Introduction

1.1 Community-Led Zero Waste Practices

Zero Waste approaches emphasise the redesign of systems to prevent waste generation and maximise resource recovery through strategies such as rethink, refuse, reduction, reuse, composting and recycling. Authors such as Connett [1] highlight that effective waste management requires not only technological solutions but also behavioural change and community engagement. Similarly, organisations such as the Zero Waste International Alliance (ZWIA) [2] and the Global Alliance for Incinerator Alternatives (GAIA) [3] advocate for systemic approaches that integrate social participation, local governance and material recovery practices. These perspectives reinforce the understanding of waste management as a socio-environmental process rather than a purely technical challenge.

1.2 The Global Ecovillage Network's Gatherings

The Global Ecovillage Network (GEN) connects ecovillages and related initiatives worldwide through regional networks [4] that coordinate activities and gatherings in different parts of the world, including GEN Europe, Red CASA Latina in Latin America, GENNA (North America), GEN Africa and GENOA (Asia and Oceania). In addition to these geographically based networks, GEN also includes transnational articulations such as NextGEN, the ecovillage youth network [5], and the GEN Elders network [6], which operate across regions as communities of practice connecting participants through events, exchanges and online collaboration. Among these, GEN Europe and the Latin American network Red CASA Latina are currently among the most extensive in terms of initiatives registered in the GEN global directory, which is publicly accessible through the online map available on the GEN website. Both networks also organize periodic continental gatherings that bring together participants from across their respective regions and beyond.

In Europe, the regional network GEN Europe [7] organizes the European Ecovillage Gathering, an annual event hosted each year by a different venue across the continent. The gathering brings together members of the European ecovillage movement as well as participants interested in regenerative living, community-based initiatives and sustainability practices.

In Latin America, the regional network of GEN is Red CASA Latina [8], where CASA stands for Consejo de Asentamientos Sustentables de América Latina (Council for Sustainable Settlements of Latin America). Beyond functioning as an acronym, the word "casa" also means "home" in Spanish and Portuguese, evoking the idea of a shared space for initiatives aligned with the ecovillage movement and with relational worldviews such as Buen Vivir, which propose a rethinking of development models based on collective well-being and harmonious relations with nature [9]. Every three years, Red CASA Latina organizes the Encuentro Continental de Comunidades (ECCO), a gathering that brings together communities and participants from across Latin America.

These gatherings bring together members of the ecovillage movement as well as participants interested in regenerative living. Participants include representatives of different GEN regional networks, volunteers involved in the organisational structures of the

network, members of ecovillages and visitors from various parts of the world, creating a highly intercultural and diverse environment where daily activities, including food preparation, accommodation and waste management, are collectively organized. For this reason, these gatherings provide valuable empirical contexts for observing community-led waste management practices.

2 Methodology

2.1 Objective of the Study

The objective of this study is to evaluate waste management practices in ecovillage gatherings in light of Zero Waste principles.

2.2 Study Context and Empirical Cases

The study draws on observational data collected at GEN's gatherings held between 2022 and 2025 in Europe and Latin America, providing a translocal perspective across different socio-cultural contexts. The sample encompasses different types of community-oriented settings, including ecovillages, eco-centres, farms and learning environments.

While not all venues are formal ecovillages, they function as temporary or hybrid community settings that host practices aligned with the ecovillage movement. During the gatherings, participants engage in shared routines, collective organisation and sustainability practices. Table 1 summarises the main characteristics of the events analysed, including their location, hosting venue and temporal scope. Geographical sub-regions follow commonly used European classifications. European Ecovillage Gatherings refer to the annual events organized by GEN Europe, while ECCO refers to the Encuentro Continental de Comunidades organized by Red CASA Latina.

Table 1. Ecovillage gatherings observed between 2022 and 2025.

Event cluster	Event date	Sub-region	Country	City	Venue
European ecovillage gatherings	7–10 July 2022	Northern Europe	Denmark	Vig	Ashram Ananda Gaorii
	12–17 July 2023	Western Europe	Germany	Schönsee	Nature Community
	20–25 August 2024	Northern Europe	Sweden	Molkom	Ängsbacka
	12–17 August 2025	Central Europe	Hungary	Lengyeltóti	Manas Garden
Encuentro Continental de Comunidades (ECCO)	1–12 February 2025	Latin America	Argentina	Cerro Corá	Reserva Natural Regenerativa La Espiral

The gatherings varied in scale, ranging from approximately 120 participants in ECCO to around 250 participants in 2022 and up to 800 participants in the European gatherings from 2023 onwards. The ECCO event also differed in duration, lasting 12 days, compared to 4 to 5 days for the European gatherings.

2.3 Research Design and Methods

The selection of the gatherings was guided by their relevance within the Global Ecovillage Network and their role as recurring continental events that bring together diverse participants and organisational structures, providing suitable contexts for observing community-led practices.

The study adopts a qualitative and multi-sited field research approach, inspired by ethnographic studies of large-scale gatherings and temporary communities, which have been analysed as sites of social organisation, cultural production and collective experience [10]. Data were collected mainly through participant observation during the gatherings, complemented by field notes, visual documentation and the analysis of on-site communication materials and participant guidelines. The study was conducted between 2022 and 2025 as shown in Table 1, indicating their temporal and geographical distribution.

3 Results and Discussion

3.1 Organisation of Labour and Collective Responsibility

Across the gatherings, different models of volunteer organisation were observed, revealing distinct ways of structuring collective responsibility. In 2022, volunteers were mobilised primarily during the event itself, without fixed teams, and participants could choose tasks flexibly as long as a minimum workload was fulfilled. In contrast, in the 2023, 2024 and 2025 gatherings, volunteers were organised as a structured "Dream Team", divided into fixed groups responsible for specific domains such as kitchen, logistics and infrastructure, operating under predefined schedules.

In the ECCO gathering, a hybrid model was observed. A core group of volunteers arrived in advance to prepare infrastructure, including dry toilets, visual communication systems and camping areas. During the event, all participants were collectively engaged in rotating teams responsible for essential daily tasks such as water supply, sanitation, kitchen support and firewood collection. This model distributed responsibility across the entire community rather than concentrating it in a fixed volunteer group.

3.2 Material Configurations and Everyday Practices

In this study, the term material configurations refers to the combination of physical infrastructure (e.g., waste sorting stations, composting systems, dishwashing stations) and informational devices (e.g., visual guidance, participant guidelines and signage) that structure how waste management practices are performed during the gatherings.

Sorting stations, composting systems, and repair/reuse initiatives are physical infrastruture, while visual guidance, participant guidelines, and signage are informational tools

that help guide pro-environmental behaviours on-site. Waste management practices were closely linked to material configurations that varied across the gatherings, as shown in Table 2.

Table 2. Summary of observed waste management practices.

Practice	European ecovillage gatherings	ECCO
Sorting stations	Present	Limited
Composting toilets	Not present (2022); complementary to water-flushing toilets (2023–25)	Central option
Composting food scraps	Present	Present
Dishwashing systems	Hand-washing with running water (2025); semi-mechanised in other years	Low-tech, water-saving hand-washing system
Volunteer organisation	Flexible participation model (2022); structured "Dream Team" teams in other years	Hybrid model with rotating collective responsibilities
Waste responsibility	Shared, with primary responsibility held by volunteer teams	Fully distributed across participants
Upcycling	Not observed (2022–2023); emerged in later gatherings as cultural activities (fashion show and permanent shop in 2024) and market fairs (2025)	Present as market and exchange practices integrated with local informal solidarity economies
Education	Not observed (2022); present as workshops and demonstrations of waste-related technologies and bioproducts (2023–2025)	Present as discussion circles and collective learning activities integrated into daily routines

In the European events, waste sorting stations and dishwashing systems were systematically implemented, with variations in technological complexity, including the use of dishwashers in some cases. In contrast, the ECCO gathering relied on low-tech solutions, such as dry toilets, manual dishwashing systems using sawdust and ash, and decentralized composting.

These configurations shaped everyday practices. For instance, participants at ECCO were required to take responsibility for non-organic waste by storing and removing it from the site, reflecting the absence of local waste collection systems. These differences suggest that low-tech and decentralised systems may encourage more direct participant engagement in waste-related practices, as responsibilities become more visible and less dependent on specialised infrastructure. In contrast, semi-mechanised systems may reduce individual involvement in certain operational tasks while increasing convenience and scalability.

Upcycling practices were not observed in the earlier gatherings (2022–2023) but became more visible in later editions (2024–2025), where they were integrated into cultural activities, markets and creative expressions, indicating an expansion of circular practices beyond waste management operations. This shift suggests that waste-related practices increasingly extend beyond management into broader cultural and economic dimensions.

3.3 Learning Practices and Circular Activities

Learning processes were embedded in daily practices and formal activities. Workshops, demonstrations and discussions on waste management technologies were included in the official programmes. In addition, practices such as upcycling markets, clothing exchange spaces and collective reuse initiatives reinforced circular behaviours. These activities extended waste management beyond technical operations, positioning it as a cultural and educational process.

Educational activities took different forms across the gatherings. In the European events, learning was mainly organised through workshops and demonstrations focused on waste-related technologies and bioproducts. In ECCO, learning processes were more closely integrated into everyday collective tasks and discussion circles. These differences suggest that educational practices may emerge through both structured instructional activities and participation in routine community responsibilities.

3.4 Socio-Environmental Configuration

The observed practices can be interpreted as an integrated socio-environmental system in which social elements and material configurations interact to enable waste management practices. Figure 1 summarises this configuration based on the empirical observations conducted during the gatherings, illustrating how social elements and material configurations interact to enable specific waste management practices and learning outcomes.

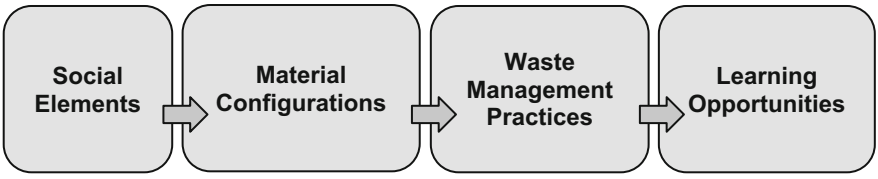


Fig. 1. Socio-environmental system supporting Zero Waste practices in ecovillage gatherings.

3.5 Implications for Waste Management

The findings indicate that waste management practices in ecovillage gatherings are not implemented as isolated technical solutions but are embedded in daily routines

and shaped by shared responsibilities, informal learning processes and community-based organisation. This alignment between social elements and material configurations appears to support the consistent performance of practices such as waste separation, composting and reuse during the gatherings. However, different technological configurations shape different forms of social engagement and learning dynamics. Low-tech and decentralised arrangements required participants to become more directly involved in waste-related tasks, whereas semi-mechanised systems reduced participation in some operational activities while facilitating larger-scale event management.

These results reinforce arguments in the Zero Waste literature that effective waste management cannot rely solely on technological efficiency [1–3]. While semi-mechanised systems facilitated the management of larger events, low-tech and decentralised arrangements required more direct participant involvement in waste-related tasks. This comparison suggests that technological solutions and social organisation are complementary dimensions of waste management rather than alternative approaches. While material infrastructures such as sorting stations and composting systems are important, their effectiveness depends on the social, cultural and organisational contexts in which they are embedded. In this sense, the gatherings operate as socio-environmental systems in which technologies are activated and sustained through collective practices.

The observations also suggest that these configurations generate collective outcomes, including reduced waste generation, effective material recovery and increased participation in waste management activities. Although these outcomes were inferred from observed practices and interactions rather than quantitatively measured, they appear to be not only technical, but also educational. Through engagement in shared practices, participants may develop greater awareness of waste-related impacts, acquire practical skills and contribute to collective capacities aligned with circular and regenerative approaches.

Moreover, these educational outcomes are consistent with Zero Waste principles such as refuse, reduce, repair, repurpose, reuse, rot and recycle, both as individual actions and as collectively enacted practices. Both the exposure to and participation in these environments may create conditions that support behavioural change and reinforce the role of gatherings as potential living learning environments.

The study therefore supports the argument that waste management practices emerge from the interaction between social organisation and material configurations. At the same time, the findings suggest that these gatherings create conditions that support social learning processes. However, given the observational nature of the research, further studies would be required to assess if these learning dynamics persist beyond the duration of the events.

3.6 Methodological Limitations

This study is based mainly on observational data, which allows for the identification of practices and learning dynamics but does not enable the assessment of long-term behavioural change. It did not include interviews or longitudinal follow-up and, therefore, educational and behavioural outcomes were interpreted primarily through observed practices and interactions during the events. Further research could explore

the persistence of these learning processes through longitudinal studies or participant follow-up.

4 Conclusion

This study sought to demonstrate that ecovillage gatherings can create environments where waste management practices are embedded in daily routines and shaped by shared responsibilities, informal learning and community-based organisation. The findings highlight the importance of aligning material configurations with social structures to support effective waste management.

The comparison between the European gatherings and ECCO also highlights how different infrastructural conditions shape distinct forms of participation and responsibility. While semi-mechanised systems supported larger-scale operations in the European gatherings, the low-tech and decentralised configurations observed at ECCO required more direct participant involvement in daily waste management activities. These differences suggest that technological complexity not only affects operational efficiency but also influences the visibility of waste-related practices and the forms of engagement they demand from participants.

These gatherings can therefore be understood as educational environments that may foster awareness, skills and collective capacities for circular and regenerative transitions.

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Educating for Net-Zero Transition: A Characterization Framework for Courses in Architecture and Engineering

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Abstract. To drastically speed up the much-needed efforts towards low-carbon and net-zero emission building and construction, we need new practices and understandings across sectors, but also across generations. New generations of practitioners should be equipped to act as change agents for a sustainable transition from the moment they graduate from architecture, civil- or construction engineering. However, literature is scarce on examples of how higher education institutions design their teaching to support this goal. This research will investigate what characterizes contemporary educational efforts for transition in the built environment and how we may describe and benchmark the current initiatives to work on improvements and supporting initiatives. The research is based on an integrative literature review whereby relevant literature is analysed for categorical similarities. The concepts identified via the analysis fall within the overarching concepts of (1) course context and scope, (2) defined objectives and outcome, and (3) activities and evaluation. Using existing tools and taxonomies these concepts are then moderated into a harmonized visualization that provides a uniform overview of the context, content and intent of a course. Such visual mapping of courses in a curriculum may help highlight where adaptations can be made, or new courses established, to improve low-carbon and net-zero efforts in higher education building and construction.

Keywords: Higher education · Teaching · Building design · Sustainable building · Taxonomy · Course design · Zero emission construction

1 Introduction

Greenhouse gas emissions and climate change are, more than ever in the Anthropocene, an imminent threat towards stability and safety. Climate science is clear on how a transition towards a net-zero emission built environment is urgent to achieve within a decade or two [1]. To this end, several practices in building, construction and real estate need to change drastically. A key role for the transition sits with the new generation of practitioners entering the field from vocational training and higher education institutions.

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They need to know the concepts, tools, strategies and collaborations needed to boost the trajectory for a net-zero built environment.

From the broader scope of including sustainable development goals (SDG) in higher education, decades of research show inspirational examples of integration into curricula and courses, combining resources from theoretical examples as well as practical projects and case studios [2, 3].

Net-zero emissions of greenhouse gases can be characterized as a sub-goal under the broader umbrella of sustainability. Likewise, the students of architecture and construction engineering represent sub-disciplinary fields of practice. Few research studies exist on that specific level of sub-goal and -discipline, where specific teaching initiatives can be detailed and concretized.

This research aims to support course designs by developing a visual framework of characterization and planning for integrating contemporary pedagogical approaches to low-carbon and net-zero teaching within the architecture and construction engineering fields in higher education. Specific guiding research questions are as follows: (1) Which characteristics of HE courses on low-carbon and net-zero can be used for a more harmonized way of communicating the content? (2) How can we use these characteristics to more visually map the educational efforts in architecture and construction engineering?

2 Research Methodology

The research builds on two core elements of first creating the characterization framework from an integrative analysis of peer-reviewed literature. Second, the framework is tested for the case of a course offered in Norwegian higher education. The framework and the outcome of testing are discussed for representativeness and for suggested future developments.

2.1 Framework Development Through Integrative Literature Reviewing

An integrative literature review was conducted to synthesize prior work and identify core aspects for the development of a characterization and planning framework. Integrative reviews combine systematic searches with qualitative and creative analyses to allow for conceptual patterns to emerge, which is highlighted as suitable for research topics that are broad and of cross-disciplinary nature [4].

The body of literature for the review was established using a search string in Scopus combining synonyms of “sustainability and low-carbon emissions” with synonyms of “higher education teaching, pedagogy and course design” and with synonyms of “architectural and construction engineering”. The systematic search was supplemented by a Scopus AI search using the prompt: “what are contemporary approaches to teaching sustainable and net-zero emission transition in higher education architecture and construction engineering?”. The two searches resulted in a list of 309 research papers that were manually screened with title and abstract. Screening criteria for inclusion in the further reading and analysis were the following: I) papers presenting frameworks or processes for integration of sustainability transition into architecture/engineering course or curricula, or II) papers presenting cross-country comparison of sustainability integration

examples, or III) papers emphasizing pedagogical aspects and activities of sustainability integration. A shortlist of 18 papers was used as the core material and referenced further in the study.

The selected literature was analysed through two integrative steps of, first, identifying dimensions used to describe the phenomenon across sources. The process served to provide a preliminary gross list of topical dimensions that were common across two or more papers. Second, the literature was reviewed to understand how these dimensions were used in the literature, and how these uses could then translate to fit the scope of this study. Based on such conceptual translation, our framework for characterization and planning was developed to reflect the core dimensions as well as the processes supporting the integration of low-carbon and net-zero perspectives into courses.

3 Results and Discussion

3.1 Dimensions for Integration in Framework

The analysis of relevant literature resulted in a set of overall course dimensions for further integration into a characterization framework. Despite the selected publications revealing a high level of heterogeneity of terminology, scope, and depth of the concepts presented, three recurring characterization dimensions for courses emerged, shown in Table 1. The three dimensions can be further described by two organisational levels containing the context within which the course sits, and the specific design elements chosen to fulfil the purpose in accordance with the pedagogical approach and vision behind. Supporting tools such as specifically tailored mind-maps and pedagogical taxonomies help define the contextual situation and the design elements. The concepts and backgrounds for the two organisational levels and the three course dimensions are specified further in the following, by reference to existing literature.

Table 1. Dimensions for describing core elements of HE courses.

Organisational levels and tools	Course dimensions	Guiding questions (examples)
Contextual situation Mind-maps to explore topical connections	1. Scope definition	How is course positioned in curriculum? Which themes will be covered and to which depth? Which competencies are emphasized?
Design elements Taxonomies for planning cognitive- and pedagogical steps	2. Objectives and outcomes	Which concepts are dealt with, at which cognitive level? How will outcome be assessed and used to iterate course structure?
	3. Activities and evaluation	How are activities structured? Which kind of learning processes do they support? How are activities and evaluations integrated?

3.2 Contextual Situation – Scope and Competencies

The context within which a course initiative is developed is crucial as stage-setting for the further detailing. Considerations here are centred around the general curriculum and the structure and content of the study programme. The contextual situation may even be perceived to supersede the study programme as such programmes are often tailored to be in line with the needs expressed by industry and society in general [5]. For example, when digitalization becomes an integral part of the construction industry, study programmes will adapt to include such new needs [6].

However, net-zero building and construction is still a broad concept, spanning a multitude of different sub-themes suitable for implementation in new or existing courses. On a contextual level, it is therefore relevant to be mindful about the wider field and prioritize those to be included in the course. Scoping can be facilitated by outlining this wider field, in a mind-mapping structure, thereafter choosing the elements for integration into a course. The mind-mapping structure suggested by Sibilla et al. [7, 8] allows for this broader overview in the shape of a pre-ordinated cognitive structure. An adapted example of such structure to the net-zero purpose is shown in Fig. 1.

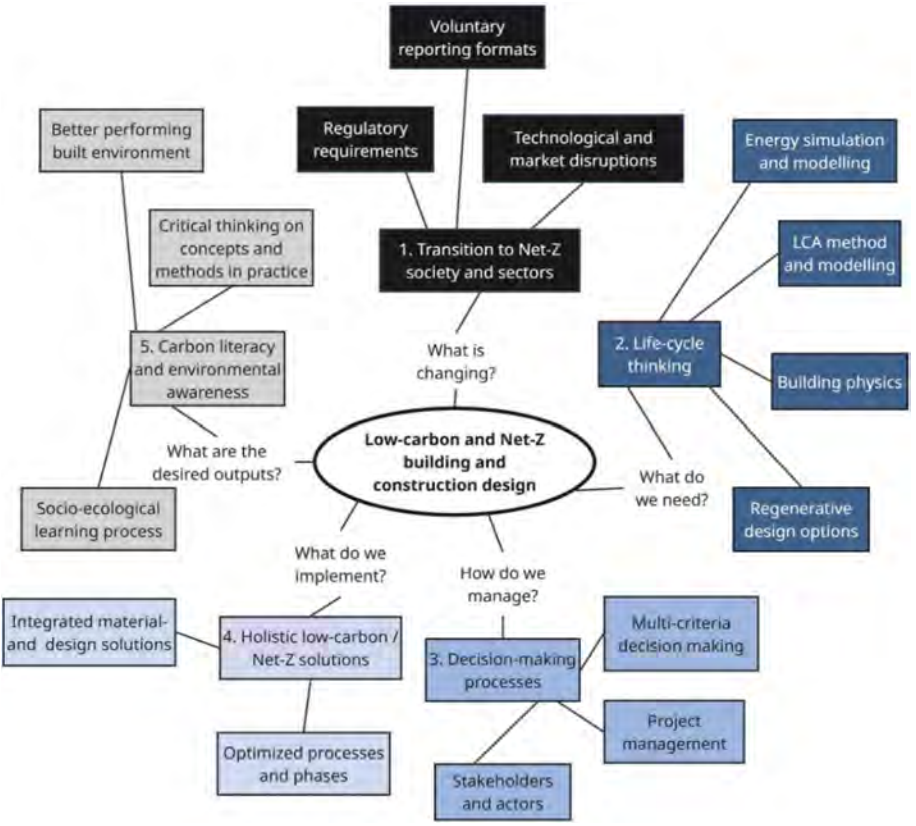


Fig. 1. Example of the wide variety of elements that can be integrated in the scope of a net-zero oriented course for architecture and building engineering. Inspired by Sibilla et al. [7].

The content scoping inherently involves parallel considerations about the level at which competencies are desired. Existing literature [9] highlights the need for students to develop sustainability-related competencies within the following: (1) Technical competencies: this includes digital tools for energy modelling or material specifications as well as methods for evaluating performance such as life cycle assessment. (2) Strategic competencies: this includes value engineering and systems thinking. (3) Interpersonal competencies: this includes interdisciplinary collaborations, communication and discussion of principles. (4) Reflective competencies: this includes ethical reasoning and integrated learning. The breadth and depth of each of these competencies are partly defined by disciplines wherein the initiative sits. For construction engineers in particular, there could be less explicit focus on developing interpersonal and reflective competencies, but more focus on the technical and strategic elements [10, 11]. Moving the agenda toward integration of more net-zero, it can be argued that such competencies are indeed valued traits. Hence, the integration of interpersonal and reflective competencies can be done more explicitly, for instance via the course design elements described more in detail in Sect. 3.3.

The contextual assessment of net-zero scope and competencies result in the specification of mission and goals, broadly describing purpose and intentions with the course. From there, more specific teaching objectives and learning outcomes can be specified in parallel with supporting learning activities and evaluation formats.

3.3 Design Elements – Objectives and Activities

As opposed to the more hidden nature of the contextual level, the specific design elements will typically be displayed explicitly as part of a course description. Such course descriptions will often detail the teaching objective (instructor's point-of-view) and the learning outcomes (student's point of view) [12]. Key elements in low-carbon and net-zero oriented courses will often relate to life-cycle thinking and life cycle assessment methods, alongside the importance of those within the application field of buildings. Further to this, course descriptions will also frequently elaborate on the main teaching activities planned as well as the evaluation criteria and examination format. Besides passive measures such as lectures and readings, application of methods like case studies as well as report writing seem to be used often in course designs for architecture and building engineering [3, 13–15].

General frameworks and taxonomies of cognitive and pedagogical processes can form the backbone for establishing the course design elements: First, by using the Bloom's adapted taxonomy for determining teaching objectives and learning outcomes for the different cognitive levels of complexity: Remember – Understand – Apply – Analyze – Evaluate – Create [13, 16, 17]. Bloom's taxonomy thus supports the definition of end goals. Second, by establishing activities as specific measures that strategically pave the way for achieving those end goals, and evaluations that seek to disclose whether the goals were achieved. Pedagogical learning design taxonomies such as the one defined by Conole and Fill [5], can assist in planning the activities throughout the course. Scholars also highlight the difference between intrapersonal and interpersonal cognition, suggesting that that co-construction through interaction with others provides greater learning outcome [18].

3.4 Course Characterization Framework – A Visual Approach

Based on the integrative literature review described in 3.2 and 3.3, the following elements, shown in Table 2, were considered important to include in a characterization framework describing the course dimensions:

Table 2. Characterizations to include in visualization framework

	What to include	Characterized based on what
The Scope	Clarity on which concepts, tools and methods are dealt with in the course	Based on wider mind-map of low-carbon and net-zero building similar to Fig. 1
The objectives and outcomes	Degree to which Bloom-taxonomy-level that learning outcomes are targeted, for each of the included concepts, tools and methods	Bloom's taxonomy [16] simplified into steps of Low, Medium and High
	Degree of disciplinarity to which the concepts, tools and methods are dealt with in the course, and how this develops from start to finish of course.	Single-focused disciplinary focus against Klein's [19] definitions of multi- and interdisciplinarity
The activities and evaluations	The type of teaching activities employed to facilitate learning from starting place and to end of course	Laurillard's [20] taxonomy for teaching activities as simplified from Conole and Fill [5] into steps of 1, 2, 3

The framework's suggested tools and categories are tested on the case of a master-level course offered at NTNU Norwegian University of Science and Technology. The purpose of this is to map the content in a structured way, thereby highlighting scope, objectives, outcomes, activities and evaluation in a format open for discussion with other scholars teaching within the same field. The case course, showcased in the framework structure in Fig. 2, brings the following elements into the scope: existing competencies from disciplines of energy simulation, PV system design, moisture and building physics and daylight are brought in from previous courses taken by students. New knowledge is added from lectures about the concepts of Net-Zero Emission Building (Net-ZEB) and the use of environmental product declarations (EPDs). For the EPDs, the basic knowledge is further used to develop whole-life-carbon calculations. Together with the other knowledge areas, this is added to a building case. The students work in multi-disciplinary teams (5–6 student in each team) to model the building. The modelling is taken to an interdisciplinary level by the several iterations and group-discussions about feasible strategies to reach a net-zero emission building, in this case by compensating material emission with expected GHGe savings from exported electricity from the PV-systems on the building.

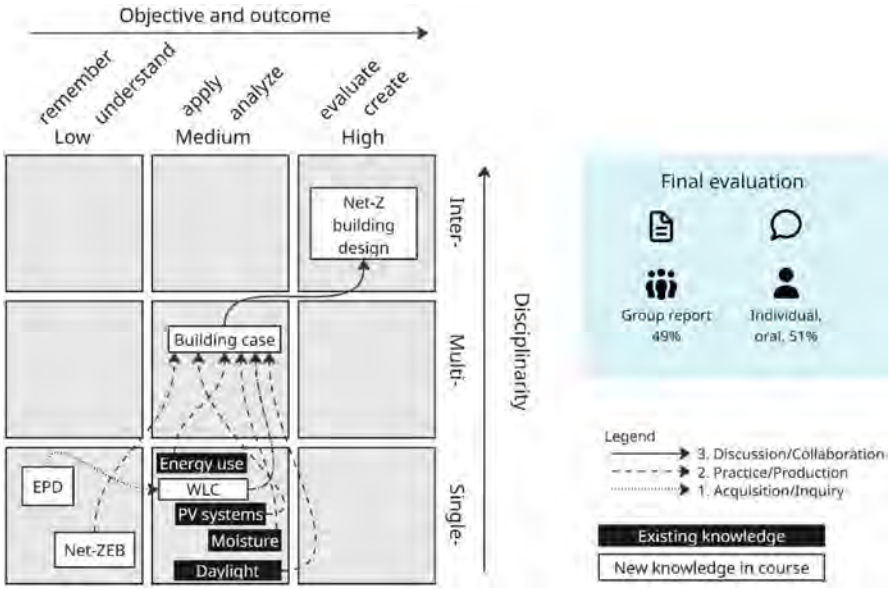


Fig. 2. The proposed characterization framework tested with the case of a course for 9th semester students on the integrated master in building engineering at NTNU

The characterization framework presents an opportunity to produce harmonized descriptions of course contents and can potentially adapt to other branches of environmental issues, for instance material circularity or design-for-disassembly. An important limitation of this study relates to the single validation on one HE course. This does not yet show how the framework performs across different institutions, disciplines, course levels, or national education systems. Such elements should be investigated further.

4 Conclusion

This study set out to advance the integration of low-carbon and net-zero perspectives in architecture and construction engineering education by developing a characterization framework for course design. Through an integrative literature review, three core dimensions emerged as central to describing and comparing educational initiatives in this field: scope, objectives/outcomes, and activities/evaluation. The framework developed from the initial analysis positions these dimensions together in a visual structure, enabling clearer communication among educators and supporting alignment between course intent, content, and pedagogical strategy. Applying the framework to a Norwegian master-level course demonstrated its usefulness for mapping disciplinary inputs. By offering a harmonized way of describing courses, the framework supports reflection, comparison, and iterative improvement across programs. Future research may further refine the framework, expand empirical testing across institutions, and explore its potential for informing curriculum-level planning and cross-course coordination.

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Regenerative Thinking in Early Design: Systemic Approaches Across Urban and Building Scales

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Abstract. This paper investigates how regenerative design principles can be integrated into built environment education through a methodology developed for an interdisciplinary studio at the Technical University of Munich. The studio positions early-phase programming—analysis, goal-setting, and concept development prior to spatial design—as the primary leverage point for embedding regenerative thinking in architectural and engineering education. The studio builds on the Regenerative Adaptive Reuse (RAR) framework, which structures adaptive reuse through three linked constructs: Adaptive Reuse Potential (ARP) as a multidimensional diagnostic lens; Regenerative Adaptive Reuse Strategies (RARS) as heuristic interventions activating building potentials; and Regenerative Urban Transformation (RUT) as a normative framework for desired socioecological outcomes. Drawing on transdisciplinary knowledge typology, the studio explicitly cultivates systems, target, and transformation knowledge across interdisciplinary teams of architecture and engineering students working on real neighbourhood transformation challenges. Students analyze obsolete buildings in urban contexts, assessing spatial, structural, regulatory, and socio-economic conditions before developing transformation scenarios. Findings across several iterations indicate that the RAR framework effectively shifts students' perception of existing buildings from constraint to resource, and that the iterative programming methodology supports genuine integration of regenerative thinking across scales. The paper concludes that structured early-phase programming offers transferable guidance for curriculum development in sustainable built environment education.

Keywords: Regenerative Design · Adaptive Reuse · Architectural Education · Circularity · Early-phase Programming · Interdisciplinary Teaching/Learning · Transition Theory · Knowledge Types

1 Introduction

The buildings and construction sector accounts for over a third of global CO_2 emissions and final energy demand, consumes approximately half of all extracted raw materials, and generates over a third of total solid waste (IPCC 2022; UNEP/GlobalABC 2024). Beyond these direct environmental impacts, the built environment shapes the physical and spatial

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structure of everyday life and thus the conditions under which sustainable ways of living become possible. As the climate crisis deepens and large portions of the existing building stock age into functional obsolescence, both practice and education have nevertheless remained anchored in incremental efficiency improvements, reducing harm rather than generating regenerative value. A more fundamental reorientation is therefore needed, one that treats the existing city as the primary resource for regenerative transformation, with adaptive reuse and neighbourhood-scale thinking as the default design logic (Reed 2007; Mang & Reed 2012; WBGU 2016; Wilkinson & Reed 2011).

This paper presents an interdisciplinary design studio at TUM embedded in the master's program Resource-Efficient and Sustainable Building (RNB), bringing together architecture and engineering students in two-semester projects focused on regenerative urban transformation. Its pedagogical design positions early-phase programming—analysis, goal-setting, and concept development prior to spatial design—as the primary leverage point for embedding regenerative thinking. A central resource is the RAR framework (Staudt & Lang 2026), which structures adaptive reuse through three linked concepts: Adaptive Reuse Potential (ARP) as a diagnostic lens; Regenerative Adaptive Reuse Strategies (RARS) as heuristic interventions; and Regenerative Urban Transformation (RUT) as a normative framework for desired socioecological outcomes. The studio draws on transdisciplinary research methodology (Pohl & Hirsch Hadorn 2008), distinguishing systems, target, and transformation knowledge as interdependent capacities, all three of which are cultivated explicitly across its phases. Building on Schade et al. (2024a, 2024b), the present work provides a more systematic account of the pedagogical framework and the design tools developed to operationalise regenerative thinking across the studio.

2 Theoretical Background

2.1 Regenerative Design and the RAR Framework

The shift from sustainability to regeneration rests on a reorientation of purpose: sustainability frameworks ask how to reduce negative impacts, regenerative approaches ask how built interventions can actively restore ecological and social systems and generate net-positive contributions (Lyle 1994; Reed 2007; Mang & Reed 2012; du Plessis 2012). For the existing building stock, this paradigm intersects directly with adaptive reuse. By retaining embodied material value, reuse projects substantially reduce lifecycle carbon and resource consumption while activating buildings as social and ecological resources (Bullen & Love 2011; Cole 2012; European Parliament 2024).

The RAR framework (Staudt & Lang 2026) operationalises this ambition by introducing ARP (latent building capacities and constraints), RUT (desired transformation outcomes), and RARS (mediating layer of heuristic strategies) linking the two to orient early-phase programming.

2.2 Space, Actors, and Scales

Spatial thinking across scales is central to regenerative design. Drawing on a sociospatial reading of urban form (Madanipour 1996), the neighbourhood analysis teaches

students to read existing spatial configurations not as neutral backdrops but as the sedimented result of historical, social, political, and economic forces—a reading that directly informs which transformations are regenerative and which merely reproduce existing conditions. Stewart Brand's layered model of building change (1994) frames how different timescales and degrees of adaptability operate within a single building (Brand 1994), while at the urban scale Gilliard et al. (2020) propose an inter-scalar, relational notion of space—understanding the city as co-produced by a variety of actors across overlapping scales and timeframes. These complementary concepts inform the studio's multi-scalar approach: one orienting students to the layered temporalities of a single building, the other to the relational dynamics of the neighbourhood and city.

2.3 Knowledge Types and Transition Theory

Regenerative design challenges, as all complex planning and policy endeavours, are inherently wicked problems (Rittel & Webber 1973; Pohl & Hirsch Hadorn 2008). They resist simple definition, involve competing values and stakeholder interests, and cannot be solved by creative design or technical optimisation alone. Transdisciplinary research methodology distinguishes three knowledge types essential for addressing such challenges (CASS/ProClim 1997; Pohl & Hirsch Hadorn 2008; Buser & Schneider 2021): systems knowledge describes empirical conditions and relationships, target knowledge articulates normative orientations, and transformation knowledge addresses strategies and competencies for enacting change. Most architectural and engineering education privileges transformation knowledge—design skills, formal repertoires, technical methods—while leaving systems and target knowledge to tacit acquisition. Teaching all three knowledge types deliberately is therefore a core pedagogical responsibility. Design studios can function as protected niches (Geels 2002), sites of socio-technical experimentation in which new practices oriented toward transition are tested and rehearsed.

3 Studio Structure and Pedagogical Design

3.1 Institutional Context

The Interdisciplinary Project (IDP) is a design studio that spans two semesters within the RNB master's program, admitting ~40 students per cohort—around two thirds from architecture, one third from engineering (civil, structural, environmental, energy). Each year a specific neighbourhood is selected as the project site, with preference for adaptive reuse and built and social contexts where authentic planning processes are underway. The studio draws on expertise from four TUM chairs—covering architecture, energy and climate, building physics, construction and fire protection—alongside external specialists in mobility, real estate development, and city administration, whose periodic reviews are embedded directly into the studio's feedback structure. The studio's structure and methodology are shown in Fig. 1.

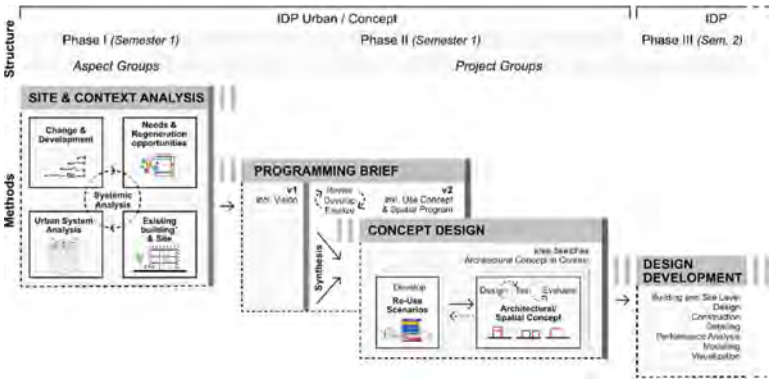


Fig. 1. Studio structure: three phases across two semesters, from (I) urban-scale Analysis (aspect teams in semester 1) through (II) Programming Brief and Concept Design (project teams in semester 1) to (III) building-scale Design Development (project teams in semester 2). Studio methods: Site & Context Analysis and building investigation feed iteratively into the Programming Brief (v1 → v2); Concept Design through synthesis of use and spatial concept.

3.2 Phase 1—Systems and Target Knowledge Through Neighbourhood Analysis

The first semester foregrounds systems and target knowledge through urban-scale analysis conducted by interdisciplinary teams. Each 'aspect team' of five to seven students investigates one of six sustainability dimensions: building structure, green-blue infrastructure, mobility, climate and energy, land use and social practices, and resources and circularity. Working through document analysis, site visits, interviews, and SWOT analyses, each team builds deep domain expertise while collectively constructing a comprehensive picture of neighbourhood conditions.

Two analytical tools structure this process (Fig. 2): (1) The layered city model disaggregates the neighbourhood into interconnected systems based on the aforementioned sustainability dimensions (2). The interdependency wheel maps these dimensions and their cross-sectoral interactions, making conflicts and synergies visible. This analysis provides students with systems knowledge. It is set against normative guiding principles—like the compact city, the inclusive city, the circular city (EC 2020; Jessen 2018; WBGU 2016)—thereby introducing target knowledge. Facilitated negotiation sessions synthesise the single aspect analyses of the different teams into a shared neighbourhood vision, grounding and informing the subsequent design work.

3.3 Phase 2—Transformation Knowledge Through Regenerative Programming and Concept Design

Halfway through the semester, the 'aspect team' members restructure into 'project teams', with all sustainability aspects represented in each project team to promote knowledge transfer and mutual learning. Phase 2 shifts focus from urban-scale analysis to building-scale programming. It opens with a systematic building analysis based on the ARP diagnostic categories (Staudt & Lang 2026), assessing existing building (following Brand's layer model (1994)), building use, physical site, urban structure and



Fig. 2. Urban systems analysis tools used in Phase 1: (1) layered city analysis (left) and (2) interdependency wheel (right). Photos: J. Staudt

context, and regulations and governance—before any design proposition is made. RARS then provide heuristic guidance for programming decisions: retention and reactivation of existing elements are explored before additions and new construction, organisational solutions are preferred over material ones. The persona method and space-time-use diagrams make visible how different user groups might share spaces across times of day, week, and year; futures thinking extends temporal awareness toward longer horizons (Wiese et al. 2014). The result is a programming brief functioning as a dynamic specification—articulating how spaces should perform, for whom, and across what range of future scenarios.

Programming and concept design develop in parallel and in mutual dependence (Fig. 1). Re-use scenarios and an emerging architectural and spatial concept are developed simultaneously, each informing and testing the other in iterative cycles: the spatial concept challenges and refines the programmatic assumptions, while the programming brief disciplines and grounds the spatial proposition. This synthesis produces a revised brief (v2)—incorporating use concept and spatial program.

3.4 Phase 3—Design Development

The consolidated programming brief and concept ground the architectural design development of the second semester, in which the project teams work at building and site level across design, construction, detailing, energy performance and lifecycle analysis, modelling, and visualisation. Proposals are tested against the ARP conditions of the existing building and evaluated against RUT objectives throughout. Feedback is structured through weekly desk crits with TUM specialists and reviews with external guest practitioners, planning authorities, and civil society actors.

4 Pedagogical Findings

4.1 From Constraint to Adaptive Reuse Potential

A consistent challenge, across studio iterations, is students' difficulty in recognising the architectural, spatial, and functional potentials of existing buildings in their urban contexts. The systematic ARP analysis begins to reverse this, but the more decisive shift

comes through direct physical engagement: sketching in situ, building physical models, and working through the layered building analysis by hand. These basic architectural tools, often undervalued against digital technologies, prove essential for developing genuine spatial understanding of existing structures. Once students can grasp a building analytically, testing spatial configurations against potential uses, they begin to experience the existing fabric as a resource—a repository of social and cultural meaning, spatial quality, and material value that can be activated.

4.2 Knowledge Types and Interdisciplinary Teams

The knowledge type structure proves pedagogically productive, though its effects are uneven and tend to follow disciplinary backgrounds. Architecture and engineering students arrive with fundamentally different disciplinary formations: architecture education tends toward open-ended, iterative, and exploratory design thinking, comfortable with ambiguity and multiple valid responses, while engineering education is typically structured around well-defined problems, approached through linear, step-by-step reasoning toward convergent, optimisable solutions. These differences surface productively in the interdisciplinary teams but also generate friction that requires explicit management.

Systems knowledge development is consistently strong across both disciplinary backgrounds, with the structured analytical tools of Phase 1 providing sufficient scaffolding for rigorous neighbourhood-scale understanding. The interdisciplinary collaboration proves particularly productive here: architecture students contribute spatial and contextual reading while engineering students bring quantitative and performance-based analysis, with each strengthening the other.

Target knowledge development is more variable: students engage productively with the RUT framework, presented as a normative orientation, but engineering students sometimes struggle with the open-endedness of articulating what ought to be, having been trained to optimise toward predefined performance criteria rather than formulate broader sustainability goals.

Transformation knowledge reveals the greatest tensions. Students with stronger analytical backgrounds, typically but not exclusively engineers, sometimes produce programming briefs of considerable depth without equivalent spatial translation, while those with stronger design intuitions sometimes bypass the programming logic entirely, producing spatially compelling proposals that lack systematic grounding. Both modes reflect underlying disciplinary shortcomings: the capacity to move fluidly between rigorous analysis and spatially imaginative synthesis is what neither bachelor-level training reliably produces on its own. The teaching team has responded by structuring interdisciplinary team roles so that this tension becomes generative rather than merely frustrating and continues to explore approaches where analytical rigour and spatial and architectural quality reinforce each other.

4.3 Interdisciplinary Competency as Transition Capacity

The studio's organisational design supports students to develop the interdisciplinary competencies that transition theory identifies as essential for system-level change

(Hölscher et al. 2021). Students consistently report growth in their capacity to communicate across disciplinary boundaries and negotiate competing priorities. The studio functions as a niche in which new professional practices are rehearsed—the systemic expert role that regenerative practice requires but existing professional divisions of labor make difficult to institutionalise.

5 Limitations and Conclusions

The studio's most persistent challenge is complexity management. The simultaneous cultivation of three knowledge types and the iterative programming methodology generate cognitive load that not all students navigate successfully. 'Analysis paralysis' is a structural risk of any format that prioritises systems knowledge over premature design closure; structured tools serve as cognitive scaffolding that mitigates but does not eliminate this risk. Institutional conditions pose a second challenge: fixed-term contracts make it difficult to maintain the teaching continuity the format requires, as transformation knowledge in teaching, like in design, resists easy formalisation and transferability. Several of the methodological elements are broadly portable, such as the RAR framework and the spatial and system analysis methods, but the informal teaching knowledge that holds the format together is harder to pass on.

The studio demonstrates that early-phase programming, structured through the RAR framework, is a key lever for integrating regenerative thinking into architectural and engineering education. The consistent shift in students' perception of existing buildings, from limitations to potentials across building and neighbourhood scales, and the development of interdisciplinary competencies as rehearsal for transition roles are its central pedagogical contributions. Making regenerative thinking, already in early project phases, an explicit focus of studio education is a key contribution that built environment curricula can make to the transition ahead.

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