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Fostering sustainability with digital twins and gamification: a systematic review

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Abstract
This systematic review investigates how digital twin technologies are combined with gamification to support sustainability across different domains. Using the PRISMA 2020 framework, we retrieved 122 records from three databases. After screening, 23 papers satisfying the inclusion criteria were analyzed in depth. Each one was examined along nine dimensions: application domain, motivation, case study, use of real-time data synchronization, digital twin type, gamification elements, visualization and interaction modalities, user involvement, and alignment with the United Nations Sustainable Development Goals. The results reveal a research landscape that is still emerging, characterized by heterogeneous methodologies, limited maturity of digital twin implementations, and a predominant use of basic gamification strategies. The findings of this review informed a set of design implications and the formulation of a conceptual framework to guide the design of gamified digital twins that foster sustainability in its various forms.

Keywords Digital twins · Gamification · Sustainability · Human-centered design

1 Introduction

The concept of digital twin (DT) has become increasingly prominent over the past two decades, largely driven by advances in Industry 4.0, cyber–physical systems, and data-driven decision-making. Initially introduced by Grieves [1] as the integration of a physical object, its virtual replica, and a data link between the two, DTs were first applied in aerospace but have since expanded into a wide range of domains, including manufacturing,

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healthcare, education, energy, and urban development. A digital twin is an intelligent virtual representation of a physical system that evolves over time by integrating sensed, historical, and simulated data, and supports prediction, optimization, and decision-making through continuous or periodic cyber–physical interaction [2]. This ability to connect physical and digital entities has positioned DTs as a transformative technology with far-reaching implications for innovation, efficiency, and sustainability [3, 4]. The integration of information technologies, such as the Internet of Things (IoT), cloud computing, artificial intelligence (AI), and big data analysis, paves the way for realizing DTs that not only provide digital representations of physical assets, but that communicate and co-evolve with them through bidirectional interaction [5].

Parallel to the rise of DTs, gamification, intended as the use of game elements and game-design techniques in non-game contexts [6, 7], has emerged as a powerful approach for enhancing interest, engagement, and learning [8]. Gamification leverages intrinsic motivation of Self-Determination Theory [9] by transforming serious and somewhat annoying tasks into enjoyable and hedonistic activities [10]. In educational and industrial contexts, gamification has been shown to improve user interaction, knowledge retention, and behavioral change [11, 12]. When combined with DTs, gamification offers a compelling opportunity to enhance user engagement in complex or technical systems, such as factory operations, energy management, or urban planning. Through visual feedback, challenges, and reward mechanisms, gamification can transform the way individuals and organizations interact with digital representations of physical systems, turning passive observation into active participation.

At the same time, the 17 Sustainable Development Goals (SDGs) proposed by the United Nations in the 2030 Agenda for Sustainable Development (see Table 1) represent a call to action for governments, industries, and academic communities, which are increasingly focused on reducing environmental impact, optimizing resource use, and promoting circular economy practices. DTs are uniquely positioned to support these goals by enabling predictive analysis, monitoring carbon emissions, and simulating resource-efficient scenarios before they are implemented in the real world [13–15]. For instance, DTs can help optimize energy consumption in manufacturing systems, design resilient urban infrastructures, or evaluate the environmental implications of construction projects. The DT technology also enables tracking and optimizing the entire product life cycle in real time, thereby ensuring their sustainable development and operation [16].

However, while existing work usually underlines the substantial technical benefits of DTs, the human dimension of interaction with DTs is rarely discussed in the literature. In the same way, the challenges related to DT adoption, fostered by user engagement and acceptance, are not addressed. Integrating gamification into DT applications can contribute to filling this gap in DT appropriation while achieving sustainability goals. Gamified DTs can engage stakeholders in energy-saving practices, encourage behavioral change towards sustainable consumption, and promote participatory decision-making in sustainable urban planning. Nevertheless, existing research remains fragmented, often addressing either the technical dimensions of DTs or the motivational aspects of gamification in isolation. Few studies systematically investigate how these two domains intersect and how their integration can advance sustainability in a measurable and scalable way.

Against this background, this paper aims to contribute to the emerging discourse by examining the intersection of DTs, gamification, and sustainability from a human-centered

Table 1 The 17 Sustainable Development Goals defined by the United Nations (https://sdgs.un.org/goals)

#	Name	Description
1	**No poverty**	End of poverty in all its forms everywhere
2	**Zero hunger**	End of hunger, food security, improved nutrition, sustainable agriculture
3	**Good health and well-being**	Healthy lives and well-being for all
4	**Quality education**	Inclusive and equitable quality education, lifelong learning for all
5	**Gender equality**	Gender equality and women and girls empowering
6	**Clean water and sanitation**	Availability and sustainable management of water and sanitation for all
7	**Affordable and clean energy**	Access to affordable, reliable, sustainable and modern energy for all
8	**Decent work and economic growth**	Inclusive and sustainable economic growth, full employment and decent work for all
9	**Industry, innovation and infrastructure**	Resilient infrastructure, inclusive and sustainable industrialization
10	**Reduced inequalities**	Reduced inequality within and among countries
11	**Sustainable cities and communities**	Inclusive, safe, resilient and sustainable cities and human settlements
12	**Responsible production and consumption**	Sustainable consumption and production patterns
13	**Climate action**	Action to combat climate change and its impacts
14	**Life below water**	Oceans, seas, and marine resources conservation and sustainable use
15	**Life on land**	Terrestrial ecosystems protection, restoration, and use, sustainable forest management, land degradation and biodiversity loss halting
16	**Peace, justice, and strong institutions**	Peaceful and inclusive societies, access to justice for all, effective, accountable and inclusive institutions at all levels
17	**Partnerships for the goals**	Implementation and revitalization of the Global Partnership for Sustainable Development

perspective. Specifically, it seeks to provide a structured analysis of existing research, identify opportunities and gaps, and highlight directions for future work. By doing so, the paper frames DTs through the lens of multimedia interaction models, ranging from traditional 2D dashboards to fully immersive extended reality environments. It draws on foundational theories of presence and embodied interaction [17, 18] and examines how these models shape the users' experience in perceiving, understanding, and acting on DT systems. These considerations also resonate with established multimedia learning principles, such as spatial contiguity and signaling, which explain how the organization of visual-spatial information influences comprehension and cognitive load [19]. This perspective aligns with established multimedia and multimodal interaction models, which highlight issues related to space perception, cognitive load, and user engagement in human-centered systems (e.g., [20, 21]). At the same time, the paper frames sustainability in line with the notion of computational sustainability [22], that is, the use of computational methods and interactive technologies to balance environmental, social, and economic objectives over time. This review, therefore, emphasizes the role of human-centered design methodologies, advanced multimedia technologies (such as virtual and augmented reality), and user engagement strategies (e.g., different types of gamification mechanisms) as critical enablers of successful and sustainable DT adoption.

This systematic review investigates how DT technologies are integrated with gamification approaches across different domains, with the goal of supporting the achievement of sustainability goals. We developed the following research questions to support our analysis of the included studies:

(RQ1) In which application domains, and with what kinds of case studies, are digital twins and gamification applied together?

(RQ2) Do digital twin systems described in the papers use real-time data synchronization?

(RQ3) Which gamification elements are most commonly employed, which are least used, and what types of combinations appear across the reviewed studies?

(RQ4) What types of visualization and interaction modalities are used in the digital twin systems described in the literature?

(RQ5) To what extent are end users involved in system design and evaluation?

(RQ6) Which Sustainable Development Goals (SDGs) are addressed by or related to the included studies?

The paper is structured as follows: Section 2 reports the related works, and Section 3 introduces the methodology adopted for this study, specifically the search process, the paper selection process, their screening, and their analysis. Section 4 presents the results according to the research questions. Section 5 summarizes the main findings, provides a set of design implications and a conceptual framework, and discusses the limitations of the work. Finally, Section 6 concludes the paper.

2 Related works

Several systematic reviews have explored the nature, role, and application of DT technologies. Barricelli et al. [2] analyze 75 papers published between 1991 and 2019, focusing on DT definitions, characteristics, and applications in manufacturing, aviation, and healthcare. Jones et al. [23] review 92 papers from 2009 to 2018 and identify 19 themes, i.e., key concepts recurring across the literature; then, research gaps and future directions are derived from these themes, including the role of DT across the product life-cycle, DT level of fidelity, data ownership, and integration between different virtual entities. In [24], a review of 115 papers published between 2002 and 2020 is presented, identifying five main topics: application contexts, life cycle, functions, architecture, and technologies. The review also highlights the challenge of developing cognitive DTs that can interact seamlessly with humans, a concept still far from realization. The review by Yao and colleagues [25] starts with analyzing the definitions of DT provided in the literature. Then, it focuses on the stages of DT development, considering a period from 1970, when the first exploration of DT technology occurred at NASA with the Apollo program, to 2020, when national policies in various countries worldwide, industrial applications, and standards related to DTs emerged. The technical features of DTs and DT application domains are subsequently analyzed. The paper ultimately highlights the most significant gaps in DT research, specifically in relation to virtual modeling technology, evaluation criteria, and the theoretical foundation of DTs. In [3], the authors generalize the definitions and characteristics of DT discussed in the literature and analyze the adopted implementation approaches for DT. Open issues for the implementation and practical adoption of DT are finally discussed, underscoring that not only technical challenges remain to be solved, but also changes in organizational culture, ways of thinking, and process models should evolve consequently.

Other reviews about DTs are mostly focused on specific domains. For instance, relying on scientific econometric methods and literature analysis techniques, the paper [26] reviews 842 studies on the application of DT technologies in architecture, engineering, and construction, with a focus on buildings, landscapes, and urban environments (BLU). It finds that DT applications are concentrated in buildings and smart cities, while the landscape sector remains underexplored. Additionally, it highlights that most current DT applications in the BLU industry concentrate on the construction and operation phases, while studies addressing their use in the design and planning stages remain limited, reflecting an underestimation of their potential in these early phases. Consequently, the authors outline future research directions that primarily apply to the design of BLU environments. Nadeem et al. [27] investigate the application of DTs in healthcare in papers published between 2019 and 2024. Specific medical fields are considered, such as oncology, cardiology, network medicine, surgery, and orthopedics, with the aim of understanding the potential of DTs for precision medicine. Indeed, DTs enable the virtual representation of patients to perform tests and simulations, including the prediction of medication efficacy. Leveraging AI-based models and IoT devices, DTs in healthcare contribute to understanding complex disease mechanisms and improving diagnostic and therapeutic approaches. The paper ultimately highlights several key challenges related to technical and ethical issues, as well as compliance with country-specific regulations for data protection and medical devices.

Within the Human-Computer Interaction (HCI) field specifically, the body of work on DTs remains limited. A literature review of 23 papers from top-ranked HCI venues (2015–2021) highlights that human–DT interaction is underexplored, with most DTs designed for workplace contexts such as manufacturing, and with minimal involvement of end users in design and evaluation [28]. This aligns with the work of Wilhelm et al. [29], which highlights that human factors in DTs are considered mostly in production planning, maintenance, teleoperation, and collaborative robotics, but rarely beyond these contexts.

In particular, few literature reviews investigate the advantages of integrating DT technologies with gamification. All these reviews are focused on specific application domains or objectives (e.g., training). For example, the paper [30] presents an overview of publications that propose the combined adoption of DT and gamification for training in industrial contexts, with the aim of outlining a project to enhance training effectiveness in the building management industry. Still in the construction industry, Tuivai et al. [31] present a PRISMA-based literature review to investigate when and how simulation and gamification are adopted to enhance lean construction methodologies. The 37 selected papers are examined through a Social Network Analysis and a content analysis, which led to the identification of DT technologies as a powerful but underrepresented approach. As a further outcome, this review highlights the importance of human-centered design methodologies that promote usability and foster system adaptability to the skill levels of the workers. The paper [32] presents a review of papers that propose solutions for manufacturing education, which integrate DT technologies with virtual learning environments, encompassing gamification-based learning. The review does not illustrate the adopted methodology for paper screening and selection, but presents an interesting analysis of the key benefits of this solution in fostering experiential learning as well as the limitations related to costly implementation, technical issues, and data privacy concerns. As a significant future goal, the review suggests the integration of human-centered values and principles into modern education systems that feature DT technologies and adaptive learning.

The sustainability dimension of DTs has also attracted increasing scholarly attention. Kamble et al. [33] systematically review 98 papers about DTs for sustainable manufacturing supply chains, linking DT features to sustainability outcomes but highlighting the lack of integration frameworks. Timperi et al. [34] examine digital twins for environmentally sustainable and circular manufacturing, highlighting how they can support industry professionals in achieving sustainability and circularity goals. The paper [16] addresses the sustainability dimension, reviewing 29 publications that illustrate the role of DTs in enhancing the product life cycle in terms of sustainable project management, green material selection, efficient energy management, predictive maintenance, component recycling, and similar aspects. The review of 50 selected papers reported in [15] describes significant energy efficiency gains from DT applications, though heterogeneity in measurement methods limited comparability. In the urban domain, Adade et al. [35] review 34 DT-based approaches to citizen participation in land-use planning, underscoring opportunities for inclusive and participatory sustainability practices. Another relevant review is provided in [36], which analyzes the role of digital transformation in advancing circular economy practices in construction.

Despite these contributions, important gaps remain. First, very few reviews focus explicitly on the intersection of DTs, gamification, and sustainability. Existing works either emphasize gamification for engagement in education and manufacturing or DTs as enablers of sustainability in supply chains and energy management, but rarely bridge the two perspectives. Second, even though most reviews recognize the importance of ethical aspects such as privacy and data protection, very few acknowledge the critical role of users in DT design and evaluation. Additionally, no comprehensive review has yet synthesized how gamified DTs can be systematically designed to foster sustainable practices and long-term user engagement. Moreover, across sustainability-oriented reviews, digital twin maturity is rarely assessed or explicitly reported. The majority of solutions appear to rely on static models or one-directional data flows, suggesting that advanced real-time or bidirectional systems capable of supporting persuasive and adaptive interventions remain underdeveloped. Our current study builds upon this body of literature by specifically investigating the intersection of digital twins, gamification, and sustainability. While previous reviews have addressed DT applications and general challenges, the environmental impact of DT solutions, or the adoption of gamification to foster DT appropriation in specific domains, none have systematically reviewed the combination of these three dimensions. By focusing on this intersection, our work aims to fill a notable gap and provide a structured overview of an emerging area that is central to both research and practice.

3 Methodology

Systematic reviews provide a structured overview of the scientific literature on a specific topic and enable the identification of open issues and challenges within the field. We followed the PRISMA 2020 guidelines [37] as a general methodological framework. Since this review is situated in the Computer Science domain, the PRISMA 2020 framework, which was originally designed for medical and clinical evidence synthesis, requires adaptation to fit the characteristics of our field. Specifically, we included the PRISMA items in this paper by reorganizing the order that the PRISMA 2020 guidelines suggest, and we adopted only those items that are relevant to an HCI-oriented systematic review. In Appendix A, the correspondence between the sections of this article and the relevant PRISMA checklist items used in this study is illustrated. A further methodological difference regards the use of the terms "Report" and "Study". In clinical research, multiple papers can be published from the same study; therefore, PRISMA separates the description of the research activity (*Study*) from the dissemination of its outcomes (*Report*). In this review, each of the included papers represents a research contribution, as all articles correspond to separate studies, and therefore, no overlap requires further clarification. Figure 1 shows the PRISMA flow diagram summarizing the outcome of the three phases: identification, screening, and selection of papers included in this review.

3.1 Identification

To explore the intersection of digital twins, gamification, and sustainability, we conducted our systematic search on three digital libraries: IEEE, Scopus, and Web of Science. The search was conducted on 21 November 2025 using the search string on title, abstract, or keywords, without any restrictions on the time of publication. The first query was meant to retrieve papers that consider *Digital Twin*, *Gamification*, and *Sustainability* simultaneously: `("digital twin") AND ("gamification") AND ("sustainability")`. This search returned only 5 results so, given the limited results, we conducted a second search, the same day and using the same digital libraries, using a broader query that was meant to retrieve papers considering only *Digital Twin* and *Gamification* at the same time: `("digital twin") AND ("gamification")`. This search returned a larger and more diverse set of studies. In fact, we retrieved a total of 122 records, which also included the five papers resulting from the first search. Out of these 122 records, we removed 31 duplicate records.

3.2 Screening

For the screening phase, we used a shared spreadsheet structured into columns for ID, digital library that returned the paper, authors, title, year, source title, digital object identifier, include/exclude, and exclusion motivation. The spreadsheet served as the platform through which each record was reviewed independently by the reviewers, who applied the IC3 inclusion criterion and the EC1 exclusion criterion, defined in Table 2, and documented their decisions.

The resulting selections were consolidated to determine which records progressed to the subsequent step. A total of 37 papers were excluded at this stage. In the second step, accord-

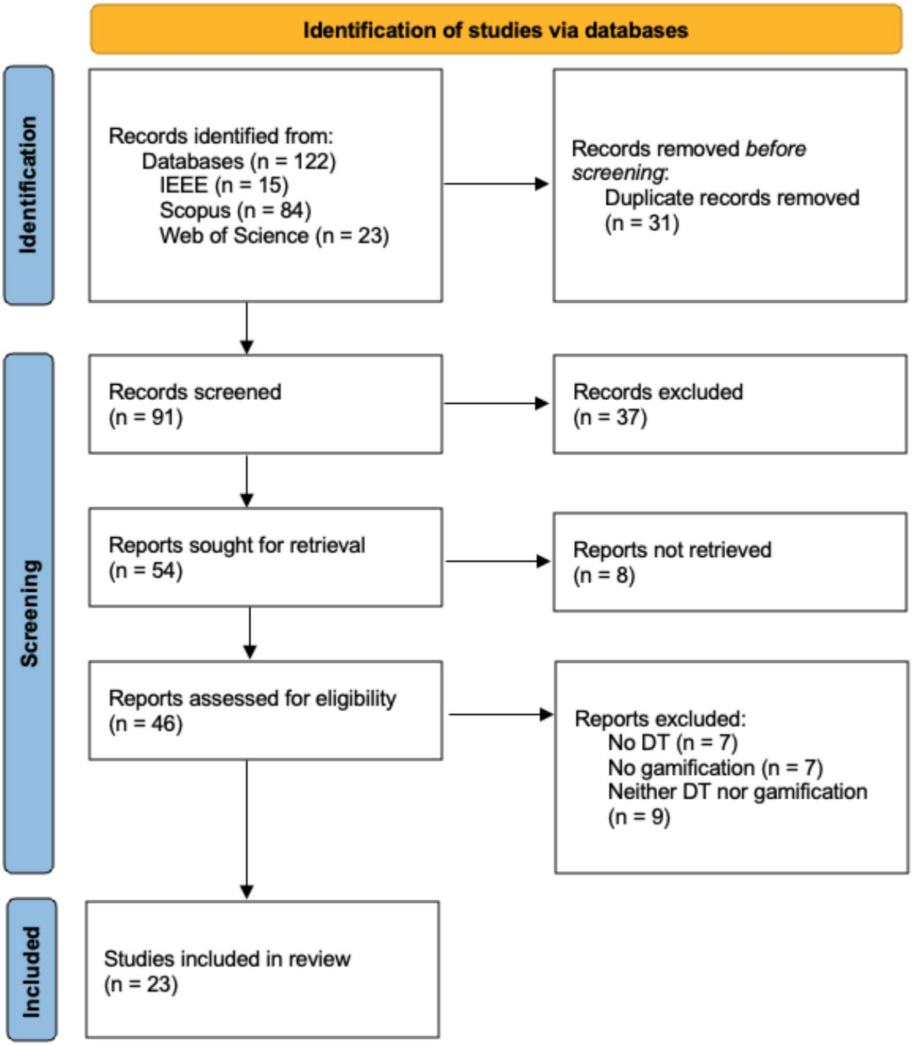

Fig. 1 PRISMA 2020 flow diagram illustrating the identification, screening, and inclusion of studies in the systematic review. The figure reports the number of records retrieved from the databases, the duplicates removed, the papers excluded at each stage based on the predefined criteria, and the final set of studies included in the analysis

ing to PRISMA 2020 flow, the reports were sought for retrieval, and we excluded 8 papers because their full texts were not available for download (criteria EC2). In the third step, the remaining 46 papers were assessed for eligibility, and 23 articles were excluded due to a lack of relevance to the study. Specifically, 7 papers were not about digital twins (criterion EC4), 7 papers did not involve gamification (criterion EC3), and 9 papers were out of scope, i.e., unrelated to both digital twins and gamification (criteria EC3 and EC4).

At the end of the screening phase, 23 papers were included for analysis.

Table 2 Inclusion and exclusion criteria adopted in this systematic review

Inclusion criteria
IC1: Focus on digital twins
IC2: Use of gamification
IC3: Paper type: conference paper, journal paper, book chapter
Exclusion criteria
EC1: Paper type: reviews, books, extended abstracts, proceeding editorials, conference description papers, or prefaces
EC2: Not retrievable
EC3: No focus on gamification
EC4: No focus on digital twins

3.3 Analysis of included papers

Table 3 reports the list of the selected papers, with their authors and publication year, classified according to the publication type: article (i.e., journal paper) or conference paper. As previously clarified, our search process did not restrict the results to the time of publication; nevertheless, it is worth noting that the oldest paper included in the study was published in 2019. This observation confirms that research combining digital twins, gamification, and sustainability is not yet mature and that scientific interest in this intersection has intensified only in recent years. Each paper was assigned to two reviewers, who independently exam-

Table 3 List of the 23 papers included in the study, authors, year of publication, and type of publication

Reference	Authors	Year	Type
[38]	Bucchiarone	2022	Journal
[39]	Ceccaroni et al.	2025	Conference
[40]	Chernbumroong et al.	2024	Journal
[41]	Dib et al.	2023	Conference
[42]	Donekal et al.	2024	Journal
[43]	Gonzalez A. et al.	2023	Conference
[44]	Hurst et al.	2025	Journal
[45]	Isoda et al.	2023	Conference
[46]	Kim	2025	Journal
[47]	Lauer-Schmaltz et al.	2024	Conference
[48]	Lee et al.	2023	Journal
[49]	Li et al.	2025	Journal
[50]	Machado et al.	2022	Conference
[51]	Munir et al.	2024	Conference
[52]	Ng et al.	2023	Journal
[53]	Olszewski et al.	2019	Conference
[54]	Park et al.	2024	Journal
[55]	Sakkas et al.	2025	Journal
[56]	Suhail et al.	2023	Journal
[57]	Terendii et al.	2024	Conference
[58]	Ulmer et al.	2022	Conference
[59]	Usman et al.	2023	Journal
[60]	Zhu et al.	2023	Conference

ined the full text and documented their assessment. When needed, the reviewers jointly reviewed specific papers to ensure a shared understanding of their suitability for inclusion.

The analysis of each article involved classifying it across multiple dimensions. Specifically, we extracted and recorded the following information in the spreadsheet, adding 9 more columns:

1. *Application domain:* Each study was categorized according to the domain in which the digital twin and gamification approach was applied, such as healthcare, urban planning, or education.
2. *Motivation:* We examined the rationale behind the implementation of digital twin technologies and gamification, for example, enhancing engagement, promoting behavior change, or supporting sustainability awareness.
3. *Case study:* We recorded whether the work included a case study, a pilot test, or any empirical deployment.
4. *Real-time data synchronization:* We verified whether the digital twin operated through real-time data synchronization with its physical counterpart or if it functioned as a simulation-based system.
5. *Type of digital twin:* The type of digital twin described in each paper was annotated (e.g., human, environmental, building).
6. *Gamification elements:* A central focus of the analysis was on the integration of gamification elements such as points, progress tracking, rewards, challenges, and feedback mechanisms.
7. *Technologies used:* We documented the technological stack adopted in each study, including hardware (e.g., sensors, devices for Augmented Reality – AR – or Virtual Reality – VR) and software platforms (e.g., AR/VR development platforms, IoT frameworks, AI engines).
8. *Users:* We assessed whether end users were involved in the system design phase, the evaluation phase, or both, particularly in studies evaluating usability, user experience, or behavioral outcomes.
9. *SDGs:* We examined whether each study explicitly addressed or contributed to one or more of the SDGs. Scopus automatically provides SDG labels for some of the selected papers, but we checked the provided information anyway. In cases where Scopus metadata did not provide an SDG classification, or the paper was exclusively found through IEEE or Web of Science, we manually assigned the appropriate SDG(s) based on the study's objectives and content.

The nine dimensions extracted from the reviewed papers were carefully mapped with the six research questions to ensure a structured and comprehensive analysis:

- RQ1: *Application domain*, *Motivation*, *Case study*, and *Type of digital twin*. This analysis examines where and why digital twins and gamification are applied, identifying the domains, the case studies, and the types of digital twins involved.
- RQ2: *Real-time data synchronization*. This analysis investigates whether digital twins rely on real-time data synchronization.
- RQ3: *Gamification elements*. This analysis examines the gamification elements adopted in the reviewed studies.

- RQ4: *Technologies used*. This analysis provides contextual details about the types of visualization and interaction modalities used in digital twin systems.
- RQ5: *Users*. This analysis focuses on the extent of user involvement in the design and evaluation processes.
- RQ6: *SDGs*. This analysis investigates the addressed Sustainable Development Goals.

4 Results

4.1 Answering RQ1: application domains

The selected papers applied DT and gamification technologies in different application domains (see Fig. 2).

Most of the analyzed papers are in the *Education* field. For instance, the research presented in [44] has an educational goal in the field of button mushroom production, thus in the more general agriculture domain. The system is designed to enable users to understand the various stages of mushroom cultivation and to serve as a training tool for new employees in the mushroom industry. The education domain is also considered in [48]; here, the goal is to improve the engagement and learning outcomes of liberal arts students in mathematics. The paper describes the evaluation of an immersive learning environment, specifically a digital twin of a math course, where game-based learning and gamification are used both in the physical and virtual worlds. The framework proposed in [38] aims to facilitate learning about complex systems and industrial processes, utilizing gamification within a VR environment to motivate users in DT training and facilitate their adoption of technology. A DT solution for education is also proposed in [50]: here, the idea is to create a system for remote laboratories in mechatronics, to support students in doing their practical activities

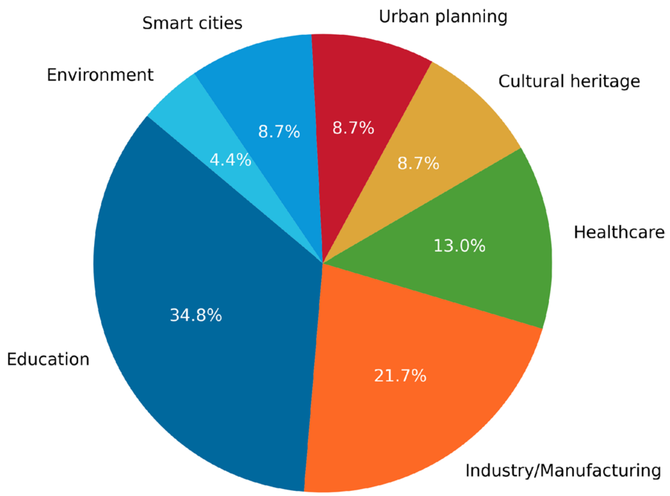

Fig. 2 Distribution of application domains represented in the 23 studies included in the review. The figure shows the frequency with which digital twin and gamification approaches are applied across different sectors, including education, industry/manufacturing, healthcare, cultural heritage, urban planning, smart cities, and environment

at a distance, without human supervision; in this case, as well, gamification is exploited to motivate students and assign them a final score. Paper [59] proposes an approach to reshaping engineering education by providing students with an immersive virtual environment, endowed with gamification, for topographic surveying. As a case study, the DT of the university campus is considered, which incorporates the 3D models of the campus buildings and their outdoor surroundings. A similar goal is pursued in [51], where the digital replica of a university library is created, allowing students and staff to take immersive virtual tours of the library and learn the book categorization system. The work presented in [43] aims to transform the classroom by offering students in industrial engineering the possibility to learn the Enterprise Resource Planning (ERP) concept. This is achieved through a digital twin that provides process simulation and gamification to foster student participation. A virtual lab for practical education and collaborative training in the field of electronic circuit design is finally proposed in [55]. In this case, the DT of the laboratory environment enables students to simulate physical activities, thereby improving the accessibility and effectiveness of learning.

Another application domain considered in the selected papers is *Industry/Manufacturing*. Paper [60] proposes a DT-based and gamified solution for the shop-floor scheduling process, to offer dispatchers in a production line a more enjoyable and effective experience. Still in the manufacturing sector, the work presented in [58] describes the implementation of DTs for gamified industrial assistance systems. A manual workstation is considered as an assistance system that supports workers in assembly activities; therefore, different DTs compose the overall architecture: the manual workstation DT providing a level-based gamification, the product DT (a door handle in this case) with its assembly work procedure, and, the user DT, which can vary according to the skills and job specification of the workers. The paper by Suhail et al. [56] studies the use of DTs in Industry 5.0, with a focus on DTs for Cyber-Physical Systems (CPSs), like critical infrastructures (e.g., nuclear power plants, power grids, petrochemical plants) and IoT-based systems (e.g., vehicles with IoT devices). In this field, since DTs are potential sources of data breaches and represent a surface for attackers to launch covert attacks, they can be leveraged to analyze security attacks to the related DT-CPS ecosystem and also provide security training and testing for users. Still related to the cybersecurity issue, the paper [42] presents a framework for developing cybersecurity DT-based simulators that take into account real-time data on user behavior during attack scenarios. To demonstrate the validity of the framework, a DT of a wastewater treatment facility is developed, which presents users with realistic cyber-attack scenarios while performing routine monitoring tasks. Kim [46] aims to study and evaluate an efficient and engaging visualization method for electric vehicles. The paper presents a simulation-based DT of an electric car, which enables users to compare the performance of electric and internal combustion vehicles and to conduct simulated driving tests under various conditions.

Two papers investigate the use of digital twins in *Smart cities*. DT-enabled smart cities are addressed in [45]; here, the idea is to use gamified 3D mobile sensing and AR to encourage citizens' participation in developing a virtual 3D city space. Paper [53] proposes the concept of *Smart City Alter Eco*, a digital twin of a town in Poland that, also thanks to gamification, can be used to test different possibilities of its development related to the construction of a biogas plant to solve environmental problems. The paper mainly defines the requirements for such a virtual environment that also has the final goal of educating citizens on sustainable development.

As to the *Environment* application domain, Ceccaroni et al. [39] present a project about the development of digital twins of oceanographic environments, leveraging citizen science for data collection. Citizens' contribution is regarded not only as a way to enhance data coverage and digital twin accuracy, but also to stimulate citizens to reflect on the impact of human activities on marine ecosystems.

The paper by Ng et al. [52] is in the related domain of *Urban planning*; gamified participatory design is studied in this case to learn about the needs of local communities and urban design problems. Still in the domain of *Urban planning*, the paper [54] proposes a framework for urban pluvial flood modeling that leverages DT technology by engaging citizens in contributing data to enhance model reliability and plausibility; gamification is one of the components of the framework, which should encourage public participation.

In the *Healthcare* domain, paper [47] explores the adoption of digital twins in the physical rehabilitation field. To enhance engagement and adherence to therapeutic exercises, a serious game is proposed that includes a human digital twin (HDT), namely a digital representation of a human capable of exchanging information with the physical counterpart, as a virtual companion in rehabilitation. The serious game provides a personalized and immersive experience, where the HDT, playing the role of the opponent, reflects the average of the patient obtained from previous sessions. Still within the *Healthcare* domain, the paper by Terendii et al. [57] presents *Touch My Heart*, a system that enables users to interact with a 3D heart model for the purposes of medical education, diagnostic visualization in collaborative discussions among professionals, and patient engagement. Training in the healthcare domain is also pursued by Dib et al. [41], who propose a VR environment for emergency response technicians that replicates a car accident scenario, offering a fully immersive experience.

Finally, the research on digital twins and gamification in the field of *Cultural heritage* is investigated in [40] and [49]. The first paper presents a study that compares a DT virtual museum environment, including gamification, with one that does not include gamification to evaluate user motivation, engagement, and learning outcomes. The second paper has a broader scope, proposing and empirically evaluating a human-AI collaboration framework that can support both experts and non-experts in developing gamified digital twins of cultural heritage sites.

4.2 Answering RQ2: real-time data synchronization

To answer this research question, we based our analysis on the digital twin maturity spectrum defined in Table 4, which we have adapted from [61]. Analyzing digital twins' maturity involves investigating the presence of real-time data synchronization and determining to which *Element* of the spectrum the DTs belong. In the last column of Table 4, we indicate the references to the papers that fall into the defined elements.

When the classification along this maturity spectrum is complete, it becomes clear that most systems feature lower maturity elements (i.e., 1 or 2), where DTs mainly act as virtual models for simulations. Only a few studies present DT endowed with elements 3 or 4, using real-time data or enabling meaningful two-way interaction. This suggests that the potential of DTs to dynamically adapt behaviors and maintain real-time data synchronization remains largely untapped. None of the papers propose DTs that enable autonomous operations and maintenance (element 5).

Table 4 Digital twin maturity spectrum (adapted from [61]) and distribution of the included studies

Element	Definition	Papers
0	Reality capture (e.g., drawings, simple 3D scans) with no functional data.	–
1	2D map/system or basic 3D model (e.g., object-based).	[49, 51, 53, 59]
2	Connected to persistent static data; Focus on simulation.	[38–44, 46, 47, 52, 54, 55]
3	Enriched with real-time data (IoT, sensors); One-way data flow from physical to digital; Focus on predictive analytics.	[45, 56, 57]
4	Two-way data integration and interaction; Focus on remote and immersive operations.	[48, 50, 58, 60]
5	Autonomous operations and maintenance	–

The following articles are focused on modeling aspects and reveal an early stage of DT development (element 1 of the spectrum). The paper by Usman et al. [59] reimagines topographic surveying as a gamified virtual environment that leverages 3D models of a university campus. The study proposed in [53] explores the concept and development of a serious game designed as part of creating a digital twin of a smart city, thus remaining at a conceptual level. The digital twin of the Chulalongkorn University central library, discussed in [51], is an immersive 3D reconstruction designed to facilitate a book classification game. The paper [49] utilizes an Artificial Intelligence-Generated Content (AIGC) framework to produce a stylized, descriptive digital twin of cultural assets, prioritizing visualization and aesthetic design over live data integration.

Additionally, several studies leverage existing data but do not explicitly emphasize the use of real-time data synchronization, instead focusing on simulation aspects or user experience in a virtual environment (element 2 of the spectrum). In the context of rehabilitation, the paper [47] utilizes performance trends derived from the user's past sessions to create dynamic digital twin-based opponents. The application described in [44] is built as a simulated educational tool, and does not currently utilize real-time data synchronization. Although the architecture is designed for extensibility, developing an accurate digital twin of mushroom growth conditions remains a future goal. Achieving this will require integrating real-time sensor data from the cultivation environment. The emergency medical technician (EMT) VR training system [41] achieves its high realism by tracking simulated user actions and physiological data within the VR environment to dynamically adjust the virtual emergency scenario. The paper [40] primarily focuses on the VR experience in a museum setting that has been digitally and realistically reconstructed by exploiting 3D models, photogrammetry, blueprint maps, and photographs of the museum objects. However, real-time data are not collected. Ng et al. [52] discuss the role of gamification in participatory design for urban planning through a VR environment that just replicates a housing estate in Hong Kong. The paper by Bucchiarone [38] explores the architecture and challenges of gamification and VR for digital twin learning and training. It focuses on simulation processes but does not mention real-time data synchronization. In [54], a framework for urban pluvial flood modeling is presented; it could utilize real-time data synchronization, but this is not explicitly highlighted in the paper. The paper by Almaguer et al. [43] focuses on an ERP simulator based on virtual and augmented reality for industrial engineering students, allowing them to analyze the processes of a car assembly company. The work proposing digital twins of the ocean [39] leverages data collected through citizen science (e.g., sporadic coastal observations) to enhance their models. While the integration of continuous real-time environmental sensor data (e.g., temperature, current) is necessary to accurately reflect dynamic changes and is a key architectural goal for these DTs, the current gamified public engagement effort primarily focuses on processing asynchronous, user-reported observations. For the digital twin electric vehicles proposed in [46], the focus is primarily on simulation and visualization of vehicle performance using a game engine. As the current implementation relies on internal simulation models and predefined parameters, it does not utilize real-time vehicle data (e.g., live battery status, operational performance) from a physical vehicle to function as an active DT of the electric vehicle. The study on cybersecurity training [42] is built around simulating attack and defense scenarios where the gamified platform utilizes simulated system status, not necessarily real-time data from a live physical system. The multiplayer virtual labs for electronic circuit design [55] is a fully digital simulation built upon the specifications of physical components; therefore, it does not use real-time data synchronization with live physical devices.

The review of the included papers indicates that only 7 out of 23 present digital twin systems that rely on real-time data synchronization with their physical counterparts for effective operation (element 3 of the spectrum). This dependency on real-time data synchronization allows digital twins to accurately reflect the current status, performance, and behavior of the physical system, which is crucial for various applications, including monitoring, optimization, training, and informed decision-making. Specifically, one-way data flow from the physical system to the digital one is implemented in 3 studies out of the 7 mentioned before. In [56], security solutions for cyber-physical systems are proposed that leverage real-time data synchronization to monitor security and operational status, enabling rapid threat detection. In [45], real-time LiDAR data collection is vital for creating 3D environmental models to enable gamified 3D mobile sensing. In the *Touch My Heart* project [57], the digital twin can synchronize physical models with real-time data to provide an accurate and interactive experience.

Finally, two-way data integration (element 4 of the spectrum) is supported in 4 papers out of the 7 presenting DTs that rely on real-time data synchronization. The system for mathematics education described in [48] employs real-time data related to user performance to personalize the learning experience and provide immediate feedback. Zhu et al. [60] propose a system that relies on real-time data from sensors and machine status to implement both monitoring and control of manufacturing processes, thereby enabling shop-floor scheduling services. The DT developed in [50], to provide remote mechatronics laboratories, requires real-time data synchronization and commands to control and reflect the status of physical equipment remotely. The study by [58] discusses the use of digital twins in manufacturing, utilizing a bi-directional data flow to integrate real-time sensor information and operational data from a physical workstation for personalized gamified feedback.

4.3 Answering RQ3: gamification elements

We structured our analysis of the gamification elements employed in the included papers using the Game Elements Hierarchy defined by Werbach & Hunter in [7]. The hierarchy organizes the elements, from the most abstract to the least, into three categories: *dynamics*,

Table 5 The classification of papers according to the Game Elements Hierarchy by Werbach & Hunter [7]. The application domain names are abbreviated as follows: H=Healthcare, CH=Cultural heritage, E=Education, UP=Urban planning, IM=Industry/Manufacturing, SC=Smart cities, EN=Environment

Paper	Domain	Dynamics	Mechanics	Components
[47]	H	Narrative, Progression, Emotions	Challenges, Feedback	Points, Progression bars, Avatars
[40]	CH	Narrative, Progression	Challenges, Competition, Rewards	Achievements, Leaderboards
[44]	E	Progression	Challenges, Feedback	Points
[52]	UP	Narrative, Relationships	Cooperation	–
[48]	E	Narrative, Progression	Rewards, Feedback	Quests, Badges, Leaderboards, Progression bars
[60]	IM	Narrative, Progression	Challenges, Competition, Feedback, Cooperation	Points, Badges, Leaderboards, Achievements
[56]	IM	Narrative	–	–
[38]	E	Progression	Challenges, Rewards	Points, Badges, Leaderboards, Progression bars
[50]	E	Progression	Feedback	Points, Badges, Leaderboards
[54]	UP	Narrative, Relationships	Rewards, Cooperation	Teams
[45]	SC	Narrative, Progression, Relationships	Competition, Feedback, Collections	Teams, Quests
[59]	E	Narrative, Progression	Challenges, Feedback	Badges
[53]	SC	Narrative, Progression, Relationships	Challenges, Feedback	Progression bars
[43]	E	Progression, Relationships	Challenges, Competition, Feedback, Cooperation	Teams, Progression bars
[57]	H	Narrative, Emotions	Challenges, Feedback	Points, Leaderboards, Time constraints
[58]	IM	Progression	Challenges, Rewards, Feedback	Points
[51]	E	Progression	Challenges, Feedback	Points, Time constraints
[41]	H	Narrative, Progression	Challenges, Feedback	Points, Achievements
[39]	EN	Narrative, Relationships	Challenges, Cooperation	Teams
[42]	IM	Narrative, Progression	Challenges, Feedback	Points
[46]	IM	Narrative, Progression, Emotions	Challenges, Competition, Feedback	Points, Progression bars, Levels
[49]	CH	Narrative, Progression, Emotions	Challenges, Rewards, Feedback	–
[55]	E	Narrative, Progression, Relationships	Challenges, Rewards, Feedback, Cooperation	Avatars

mechanics, and *components*. Table 5 reports, for each of the included papers, its application domain and the gamification elements used for each of the categories in the hierarchy.

The elements comprised in the *dynamics* category represent the big-picture aspects that have to be designed in a gamified system, but cannot be directly placed in the system.

Across the reviewed papers, dynamics commonly emerge through *Progression*, *Narrative*, *Relationships*, and a few times through *Emotions*. *Progression* is the most recurrent dynamic: it structures learning or operational processes in rehabilitation [47], mushroom education [44], mathematics learning [48], shop-floor scheduling [60], and various DT-based training systems [38, 41–43, 46, 50, 51, 58]. *Narrative* plays a prominent role in cultural and contextualized experiences, such as VR museum exploration [40], participatory housing design [52], smart city environmental simulation [53], emergency response training [41], cybersecurity scenarios [42], and AI-driven cultural heritage revitalization [49]. Dynamics grounded in *Relationships* emerges in collaborative or socially oriented DT applications, including co-design frameworks [52], flood-modeling participation [54], multi-team sensing activities [39, 45], educational cooperation [43], and multiplayer laboratory environments [55]. Finally, *Emotions* are evoked in systems that rely on immersion, self-challenge, or affective engagement, particularly in rehabilitation [47], mixed reality heart exploration [57], and stylized cultural experiences [46, 49]. Together, these dynamics illustrate how gamification in DT systems often builds its motivational structure around narrative and structured development, as well as social or emotional engagement.

Mechanics are the basic processes that lead to player engagement. Mechanics across the included studies consist of *Challenges*, *Feedback*, *Competition*, *Rewards*, *Cooperation*, and, in just one case, *Collections*. *Challenges* are among the most commonly used mechanics, shaping rehabilitation support systems [47], DT-enhanced VR museum interaction [40], educational gameplay [38, 44, 48, 51], industrial scheduling [58, 60], topographic surveying tasks [59], ocean-monitoring participation [39], emergency medical simulations [41], cybersecurity training [42], vehicle simulation scenarios [46], and cultural heritage [49]. *Feedback* is almost equally present, appearing as real-time or event-driven responses that guide user action and reflection in rehabilitation [47], educational DTs [44, 48], industrial environments [53, 58, 60], surveying training [50, 59], virtual laboratory collaboration [55], and cybersecurity [42]. *Competition* emerges in museum classification tasks [40], team sensing [45], cooperative and competitive learning [43], and vehicle comparison [46]. *Rewards* are used to motivate user progression in museums [40], mathematics education [48], DT-based training [38], urban planning [54], and cultural heritage revitalization [49]. *Cooperation* is central in participatory housing design [52], collaborative labs [55], environmental data collection [39, 54], and multi-role VR education [43]. *Collections* appear just once in LiDAR-based mobile sensing [45]. Overall, mechanics demonstrate how DT gamified systems base their user engagement process on well-known motivational elements.

Components represent the concrete form in which mechanics and dynamics can be implemented. The elements in this category that appear frequently are *Points*, *Progression bars*, *Leaderboards*, *Badges*, and *Achievements*, followed by elements that are adopted a few times: *Teams*, *Quests*, *Time constraints*, *Avatars*, and *Levels*. *Points* are used in a wide range of applications, from rehabilitation [47], mushroom education [44], and mathematics learning [48] to shop-floor gamification [60], topographic surveying [57], emergency response [41], cybersecurity training [42], and DT-based electric vehicle visualization [46]. *Progression bars* serve as continuous indicators of advancement in rehabilitation [47], mathematics education [48], industrial support systems [43, 53], and electric vehicle simulation [46]. *Leaderboards* appear in competitive museum experiences [40], mathematics education [48], industrial manufacturing [60], topographic surveying [57], and learning complex system management [38]. Long-term engagement is reinforced by *Badges* in education [38, 48, 50, 59] and by *Achievements* in museums [40], industry [60], and healthcare [41]. *Teams* underpin collaborative and learning activities [39, 43, 45, 54]. *Quests* emerge in smart cities [45] and mathematics education [48], while *Time constraints* add challenge or urgency in surveying and learning contexts [51, 57]. Finally, *Levels* extend progression in industry [46], and *avatars* support embodiment in education [55] and healthcare [47].

4.4 Answering RQ4: visualization and interaction modalities

From a multimedia and HCI perspective, visualization and interaction modalities are not just implementation details, but concrete responses to what users expect to engage with within a digital twin. As widely discussed in multimodal and multimedia interaction literature (e.g., [20, 21]), different interface modalities, such as 2D dashboards, 3D desktop environments, VR, AR, or mixed reality (MR), require different cognitive demands and provide different engagement levels. Theories of embodied and immersive interaction (e.g., [17, 18]) highlight how varying degrees of immersion, embodiment, and sensory richness enhance users' attention and experiential involvement. These modalities shape which aspects of the physical system become salient, how easily users can navigate complex data, and which kinds of activities can be supported (e.g., monitoring, exploring, training, or decision-making). Accordingly, the visualization and interaction approaches used in the reviewed studies are discussed in what follows.

Out of the 23 included papers, only three ([39, 48, 56]) do not provide information about the interaction and visualization techniques chosen for their systems. Among the other 20 papers, there are nine 3D systems designed for use on desktop PCs, four VR systems, four MR systems (featuring both VR and AR), one AR system, one dashboard-based system, and one 2D system that uses avatars.

Considering the 3D systems, the project Digital Commons presented in [52] uses a digital community game approach to support the participatory design of high-density housing estates. To this aim, the game is developed as a web-based 3D interactive system that does not require any VR device, because it does not provide an immersive experience. The system for remote mechatronics laboratories presented in [50] provides students with a system to perform laboratory activities remotely. The system provides the students with multiple environments; among these, there is the so-called "Virtual setup", a virtualization module aimed at showing the state of the student's activity in the laboratory. Furthermore, students can access a screen with a 3D virtualization developed using Unity. Similarly, the *DigiFungi* education software for button mushrooms described in [44] is implemented as a first-person controller environment using Unreal Engine and Blueprint. It is not focused on immersive experience, but the intention was to provide a tool that gamifies a complex process, abstracting it to inspire and educate. In [54], a framework for urban pluvial flood modelling is presented. The users, in a participatory setting, can access a 3D visualization of the territory, interacting with the system via keyboard, mouse, or touch if on mobile devices. An interactive web application for topographic surveying integrated with gamification elements is presented in [59]. The system implements three computer-generated environments and incorporates 3D Building Information Modeling (BIM) models of buildings and surroundings. The system has been implemented with Unity 3D, Autodesk Revit, 3DS Max, and Blender for modeling the 3D environments. In [53], the authors present a prototype of a serious game that extends the *Cities: Skylines* engine (Unity 3D-based). In the game, the users can impersonate the mayor, a poultry producer, or a resident, in a digital twin of a Polish city called Zuromin. By assuming different roles, the users can experience the simulation of decision-making processes, supported by 3D visualizations of the territory and dynamic environment data. Unity 3D has also been used to develop the DT of an electric vehicle to enable the simulation of a driving environment and test various scenarios [46]. The interaction takes place on a desktop PC, supporting both first-person and third-person perspectives.

The 3D virtual library described in [51] has been developed as a multiplayer game in Unity: users can interact with an animated information box, pick and place virtual books, take virtual tours by walking, running, or jumping, and participate in book classification by means of a book sorting game. A framework for developing immersive experiences with cultural heritage sites is proposed in [49]. Here, generative AI tools - e.g., Stable Diffusion, GPT-4.5, Midjourney - are combined with traditional methods for 3D modeling, content creation, and gamification logic design, to support both experts and non-experts in developing an interactive VR/AR application in Unity.

As to the four papers discussing VR systems, the study reported in [40] is about the use of gamified VR in virtual museum environments. The idea is to offer personalized and immersive experiences, with the aim of fostering engagement. The authors believe that VR has the potential to provide enriched learning experiences and elicit positive emotional responses, as well as higher satisfaction, pleasure, and enjoyment, in this application domain. Due to the authors' interest in providing a high level of realism and interactivity, the system was implemented using the Unity Game Engine, Blender, and RealityCapture for producing the 3D models. To access the VR system, users have to use the Meta Quest 2 headset. The virtual lab environment described in [55] has been developed as a Unity multiplayer game. The environment presents itself as a workshop room with circuit components placed over tables, where users can collaborate, performing shared actions through their avatars and using voice communication. The VR environment for emergency medical technicians [41] is an application developed using the Unreal Engine, which provides visual, audio, and haptic feedback. User-system interaction utilizes the Meta Quest headset, and data on users' heart rates is collected to enable stress detection. The work by Bucchiarone is a conceptual paper [38]; therefore, it does not provide information about interaction and visualization development. However, the author provides their vision for combining gamification and virtual reality as a means to support digital twin learning and training.

MR systems have been proposed in four papers. In [57], the *Touch My Heart* system is presented as a digital twin that offers mixed reality interaction to immerse users in exploring the human heart. The system is designed for healthcare professionals who can interact using a Magic Leap 2 headset and, thanks to hand tracking and haptic feedback, via the UltraHaptics device. The immersivity of the system is enhanced by the use of spatial audio cues. Almaguer et al. [43] present an ERP simulator that offers mixed reality interaction, aiming to facilitate the learning process of industrial engineering students. The application is web-based and can be used individually or as a team. Unfortunately, the paper does not provide any further information about the interaction or the visualization of the elements in the system, especially to what concerns the devices used for implementing VR and AR in the mixed reality setting. The work of Ulmer et al. [58] is a conceptual paper that proposes the use of digital twins to create industrial assistance systems that incorporate gamification elements. The authors claim that they tested the concept in a physical Industry 4.0 model factory at a university, using an AR-enhanced manual workstation and a VR training environment. No further information is provided in the paper about the equipment or tools used for this test. Oculus Quest 2 is adopted in [42] to provide users with fully immersive, interactive simulations of cyber-attacks on critical infrastructures. Users can interact with the DT with both VR and AR interfaces. VR allows for reproducing and experiencing the environment (e.g., a wastewater treatment facility) in an immersive way, and AR is implemented by overlaying threat information onto a miniature physical testbed created with

Arduino components. Additionally, generative AI based on GPT-4o is adopted both to tailor cyber-attack scenarios based on user expertise and to provide real-time feedback.

The gamified system for shop-floor scheduling service presented in [60] has been developed using Mendix, a low-code application development platform. Although the authors do not clearly describe the interaction details provided in the system, from the pictures shown in the paper, the reader can see that the user interacts with a gamified dashboard.

Isoda et al. [45] present a preliminary study of a gamified AR mobile sensing system, aimed at collecting 3D spatial information from LiDAR-equipped mobile devices, through an AR coloring game. The prototype developed so far has been implemented for iPad Pro devices through the Apple ARKit framework.

In [47], HDTs in serious games are explored, trying to balance between realism and engagement, and at the same time ensuring ease of interaction. The case study is based on the Badminton game, where the *Ghost Opponents* concept is implemented: the user can play against a recorded past performance of themselves. To interact with the game, and therefore play it, only the user's elbow movements are tracked using a camera-based motion tracking algorithm by Google. The 2D visualization of the players on the screen is implemented using avatars created with the *Ready Player Me* tool.

Overall, the reviewed systems can be categorized into three multimedia interaction patterns. First, dashboard-style 2D interfaces that offer low-cost access, but also limited support for embodied exploration of the DT. Second, 3D desktop environments that provide richer visualization while still relying on conventional mouse–keyboard interaction, thus balancing familiarity with increased cognitive load. Third, immersive MR settings emphasize presence, bodily engagement, and multi-sensory feedback, which is particularly useful in training, healthcare/rehabilitation, and cultural heritage scenarios. However, only a few papers explicitly justify these choices in terms of user needs or accessibility, and almost none of the papers discuss issues such as motion sickness, 3D-blindness, 3D-fatigue, or hardware constraints. This suggests that multimedia design in DT–gamification systems is often driven by technological opportunity rather than by explicit human-centered reasoning about user needs, skills, and background.

4.5 Answering RQ5: End user involvement

As a further investigation, we sought to determine whether the selected papers provide information about user involvement in design and/or evaluation. However, we noticed that more than half of them provide limited or no information about this aspect, sometimes because of the preliminary nature of the designed or developed systems.

Users have been involved in different phases of the project described in [47]. Firstly, several conversations with 15 stroke patients allowed the researchers to clarify their research question and the requirements for game design. Then, 10 healthy individuals were involved in a preliminary study with the first prototype, which required participants to play four consecutive 3-minute rounds of the game and then discuss the outcomes in a semi-structured interview. The study involved a limited number of participants, but the authors indicate that, as future work, they intend to conduct further evaluations with a broader and more diverse population, including participants with varying physical disabilities.

Almost all phases of the project development described in [52] included the participation of end users: in the first phase, 12 non-architecture students used a multiplayer board game for urban design to study the context and residents' needs; in the second phase, 4 architecture students participated in designing the wet market area, with the purpose of assessing the feasibility of a VR environment representing an immersive digital twin of the urban site; the third phase of the project involved 12 older adult residents and 4 architecture students divided into four groups with the goal of co-creating a wet market design through an improved version of the game.

Paper [48] describes the evaluation of the effectiveness of a digital twin for math education with 218 students. As for system design, it is not extensively described in the paper, but a committee was formed to study gamification content that fits students' backgrounds. Similarly, several students (about 350) and expert surveyors (about 20) have been involved in the evaluation of the educational game discussed in [59]; their qualitative feedback, obtained through twelve survey questions, was collected to improve the next version of the system; in addition, 15 students answered to the System Usability Scale (SUS) questionnaire, leading to a good evaluation of the system usability. During system design, faculty members teaching topographic surveying contributed to the specification of the virtual environment by supporting developers incorporating 3D models of buildings and outdoor surroundings into the system.

In [49], six participants (four experts and two non-experts) were divided into three groups and involved in a comparative test of different workflows employed in the design of a model for a cultural heritage site, representing the first step of the development of the gamified digital twin. Direct observation and final interviews were used to evaluate the workflows in terms of creativity, work efficiency, and potential enhancements to the tools. Subsequently, a panel of six specialists and 122 generic users evaluated the final models along several dimensions: cultural authenticity, visual appeal, technical details, innovation, and usability.

To assess the impact of gamification on motivation, engagement, and knowledge acquisition, the paper [40] presents a study that involved 76 undergraduate students in human-related disciplines (38 testing the gamified VR solution, 38 testing the system without gamification); the controlled experiment was conducted in a laboratory environment. However, the same paper does not provide any information about the involvement of representative end users in the design and development of the compared environments.

The design of the ERP simulator with gamification presented in [43] was informed by the results obtained from a previous version with approximately 320 students. The new system was evaluated with 26 students, considering the grades obtained before and after its adoption. Results proved that the increase in student learning using the simulator with gamification was statistically significant.

A small-scale pilot study involving 12 undergraduate students was performed to evaluate the virtual lab platform for electronic circuit design [55]. Participants were divided into two groups based on their previous experience in the field. After completing the assigned tasks, participants were asked to fill out an ad-hoc questionnaire that assessed several aspects related to usability, perceived learning, and cognitive engagement on a Likert scale. Results were very positive, and no statistically significant differences emerged between the groups, demonstrating the suitability of the DT regardless of users' level of familiarity with it.

The information gathered through structured interviews with mushroom experts informed the design and development of *DigiFungi* [44]. The paper, however, describes a preliminary stage of the project, whose final goal is creating the DT of a mushroom; therefore, only an alpha test was performed with 10 participants, who were required to answer questions about the proof-of-concept's user-friendliness, completeness, performance, innovation, and helpfulness for training.

The following 14 papers, instead, do not provide or provide very limited information about user involvement in the research.

The work presented in [45] is a preliminary study on 3D mobile sensing using gamification to encourage citizens in participation; due to the preliminary nature of the work, only initial experiments were performed in the laboratory, one with two players and another with four players; user involvement in system design is not mentioned in the paper. Citizen participation is fundamental also for the success of the project described in [39]. The created platform includes tools, applications, and digital twin implementations of the ocean, but their evaluation with users is not discussed in the paper. Similarly, the crucial role of citizens is highlighted in [54], which discusses participatory urban flood modeling. However, at the current stage of the research, only available data sources and services contributed to the case modeling presented in the paper. As future work, it is planned to develop an online crowdsourcing platform for citizen participation in flood modeling. The authors of the paper [60] stated that the requirements for the gamified DT-based solution were derived from preliminary research and interviews with dispatchers from various enterprises, namely the domain experts in the shop-floor scheduling process. However, the paper does not provide details about the involvement of users in the subsequent phase of system development, neither for design nor for evaluation. The paper [56] presents a proof-of-concept of a gamified DT for CPS security, but users were apparently not involved in its design. Validation was performed with available datasets; users were not considered for evaluation, probably due to the proof-of-concept nature of the system. Similarly, paper [38] only presents an agenda and an architecture for learning/training activities; therefore, no evaluation with users is available. However, the paper mentions the need to involve various types of experts in preparing and selecting training materials, as well as tailoring the gamification elements to the case at hand and its users. Conducting tests with users (i.e., students) is envisioned as the next stage of development of the work presented in [50]. This paper describes the design and implementation of a system for remote laboratories at a university, but does not discuss the involvement of teachers or students in the design. Likewise, the virtual library developed in [51] has not been apparently designed following a human-centered approach, and its evaluation is planned as future work. The same is true for paper [42], where the proposed platform was apparently not designed with user involvement, and the authors state that a user study on the platform will be performed. Paper [53] only conceptualizes the idea of a smart city digital twin enriched with gamification to test different scenarios; thus, users have not been involved yet, neither in design nor in evaluation. Although at a more advanced stage, paper [57] also does not discuss any evaluation of the proposed system for immersive exploration of the heart; however, the authors state that the heart model was validated by a cardiologist. Evaluation with users is planned as a follow-up research in the work presenting the DT of an electric vehicle [46]. Users (namely, first responders) have not been involved in the design or evaluation of the system supporting training in emergency medical situations described in [41]. Finally, paper [58] does not mention the involvement of workers in the design of the gamified solution for assembly assistance in manufacturing, nor discusses any evaluation with users; it only considers as future work the need for monitoring workers' system acceptance.

4.6 Answering RQ6: sustainable development goals

Each of the 23 included papers has been associated with at least one of the SDGs (see Table 6).

The highest number of SDGs associated with a single paper is 7, while the lowest is 1, which occurred for 7 out of 23 papers. The average number is 2.83 while the median is 3.

The paper with the highest number of associated SDGs is [44]. Specifically, the paper topic is connected with seven themes: Zero hunger (SDG 2), Good health and well-being (SDG 3), Quality education (SDG 4), Industry, innovation and infrastructure (SDG 9), Sustainable cities and communities (SDG 11), Responsible consumption and production (SDG 12), and Climate action (SDG 13). Another paper ([49]) is associated with six SDGs: Quality education (SDG 4), Industry, innovation and infrastructure (SDG 9), Reduced inequalities (SDG 10), Sustainable cities and communities (SDG 11), Peace, justice, and strong institutions (SDG 16), and Partnerships for the goals (SDG 17). Five SDGs are linked to paper [46]: Affordable and clean energy (SDG 7), Industry, innovation and infrastructure (SDG 9), Sustainable cities and communities (SDG 11), Responsible production and consumption (SDG 12), and Climate action (SDG 13).

Figure 3 shows how many times the SDGs are associated with the included papers. The most recurrent is SDG 9 (Industry, innovation and infrastructure), associated with 14 papers ([39, 41–44, 46, 47, 49–51, 55, 56, 58, 60]), followed by SDG 4 (Quality education) with 13 occurrences ([38, 41–44, 48–51, 53, 55, 59, 60]), and by SDG 11 (Sustainable cities and communities), connected with ten papers ([40, 41, 44–46, 49, 51–54]).

Table 6 SDGs associated with each included paper

Paper	SDG(s)
[38]	4
[39]	9, 13, 14, 17
[40]	11, 17
[41]	3, 4, 9, 11
[42]	4, 9, 16
[43]	4, 9
[44]	2, 3, 4, 9, 11, 12, 13
[45]	11
[46]	7, 9, 11, 12, 13
[47]	3, 9
[48]	4
[49]	4, 9, 10, 11, 16, 17
[50]	4, 9
[51]	4, 9, 11, 16
[52]	10, 11, 16
[53]	4, 8, 11, 12
[54]	6, 11, 16, 17
[55]	4, 8, 9
[56]	9
[57]	3
[58]	9
[59]	4
[60]	4, 8, 9

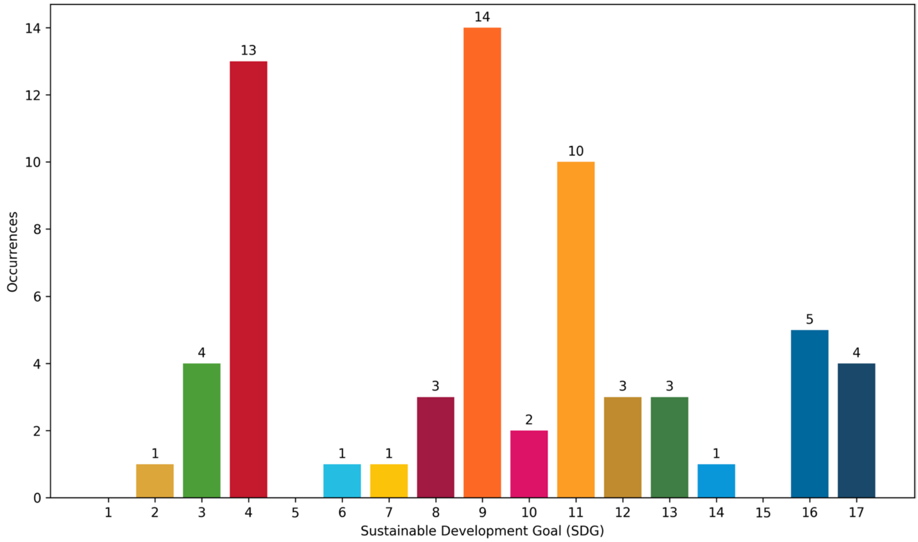

Fig. 3 Frequency of Sustainable Development Goals (SDGs) associated with the 23 studies included in the review. The figure reports the number of papers linked to each SDG, based on Scopus metadata and manual verification

Figure 4 presents a heatmap showing all occurrences and co-occurrences. The numbers on the main diagonal (from top left to bottom right) indicate the number of occurrences for each individual SDG, while the off-diagonal cells indicate the co-occurrences between pairs of SDGs. The darker the colour, the higher the number of (co-)occurrences.

The distribution of Sustainable Development Goals across the included papers reveals a characteristic pattern that aligns with the early-stage nature of research at the intersection of digital twins, gamification, and sustainability.

The SDGs that occur the most are SDG 9 (Industry, innovation and infrastructure) associated with fourteen papers ([39, 41–44, 46, 47, 49–51, 55, 56, 58, 60]), SDG 4 (Quality education) linked to thirteen papers ([38, 41–44, 48–51, 53, 55, 59, 60]), and SDG 11 (Sustainable cities and communities) connected with ten papers ([40, 41, 44–46, 49, 51–54]), and SDG 16 (Peace, justice and strong institutions), associated with five papers ([42, 49, 51, 52, 54]).

Regarding the co-occurrences, the most frequent SDG pair is constituted by SDG 4 and SDG 9, associated with nine papers ([41–44, 49–51, 55, 60]). The other pairs that occur more frequently are SDG 4 and SDG 11, associated with five papers ([41, 44, 49, 51, 53]), and SDG 9 and SDG 11, also associated with five papers ([41, 44, 46, 49, 51]).

These three SDGs (4, 9, and 11) occur together four times ([41, 44, 49, 51]), while SDGs 4, 9, 11, and 16 are linked to two papers ([49, 51]).

Environmental SDGs such as SDG 7 (Affordable and green energy), SDG 12 (Responsible consumption and production), SDG 13 (Climate action), and SDG 14 (Life below water) appear less frequently and mostly in conjunction with larger multi-SDG groupings. Their occurrence suggests that environmental applications of digital twins and gamification are present in the papers included in this study, although they remain limited. Also, it is worth

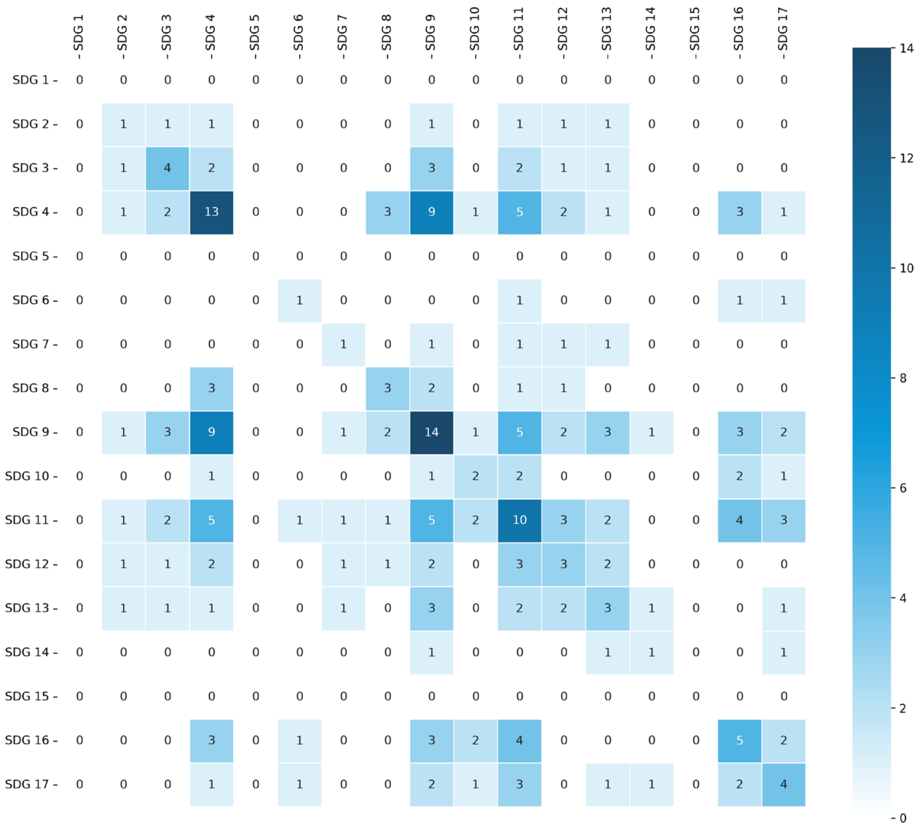

Fig. 4 Heatmap of SDG occurrences and co-occurrences across the 23 included studies. Diagonal cells represent the number of papers addressing each individual SDG, while off-diagonal cells display the frequency with which pairs of SDGs are jointly associated with the same study. The colour scale ranges from white (null or low occurrences) to light blue (medium occurrences) and blue (high occurrences), indicating the intensity of each (co-)occurrence

noting that SDG 1 (No poverty), SDG 5 (Gender equality), and SDG 15 (Life on Land) are not represented at all in the included papers.

4.7 Cross-RQ analysis

From a human-centered perspective, cross-analyzing application domains, SDGs, gamification elements, and real-time data synchronization allows us to understand not only where the DTs are implemented the most, but how the design of their multimedia interfaces and engagement features can support sustainability.

A cross-RQ analysis of the application domains (RQ1) and the SDGs (RQ6) associated with each included paper reveals that each domain is linked to a specific cluster of sustainability goals, rather than contributing to several SDGs. Figure 5 shows how each application domain is connected to the SDGs addressed in the 23 included papers.

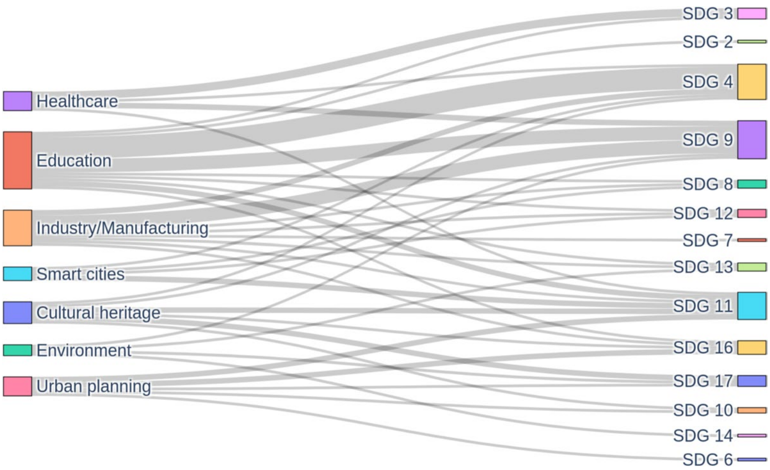

Fig. 5 The relationships between application domains (left) and the Sustainable Development Goals (right) addressed by the papers included in this study. Each flow represents the number of papers linking a given domain to a specific SDG. The visualization highlights how different domains tend to converge on distinct sustainability goals

Education is the most common domain in this study and maps to SDG 4 (Quality education), often in combination with SDG 9 (Industry, innovation and infrastructure). This means that DT-based learning platforms primarily contribute to sustainability through skill development rather than through environmental impact. The second most common domain is *Industry/Manufacturing*, always aligned with SDG 9, and in some cases (those that present DT applications that support the learning process of workers) with SDG 4. Only one paper belonging to this application domain is linked with environmental sustainability, namely SDG 12 (Responsible consumption and production) and SDG 13 (Climate action). The papers clustered in the *Smart cities* and *Urban planning* domains have, as expected, a strong connection with SDG 11 (Sustainable cities and communities). It is worth highlighting that the two papers in the *Urban planning* domain are linked to SDG 16 (Peace, justice and strong institutions) and one of these is also connected with SDG 17 (Partnerships for the goals), suggesting that their sustainability impact is towards citizen engagement and collaborative decision-making. The papers in the *Cultural Heritage* domain are linked to SDG 11 and SDG 17, highlighting how digital twins and gamification are used to support cultural valorization and public engagement. The three papers categorized in the *Healthcare* domain are consistently associated with SDG 3 (Good health and well-being). Only one paper results being classified in the *Environment* application domain; it is associated with SDG 13 (Climate action) and SDG 14 (Life below water). The outcomes of this cross-RQ analysis suggest that the literature tends to address sustainability with a domain-dependent approach rather than directly targeting environmental sustainability outcomes. Overall, these findings reflect an emergent research area in which sustainability is interpreted more as a structural and behavioral challenge addressed through innovative learning technologies, rather than as a direct intervention on the environment.

The exploration of another cross-analysis, between the application domains (RQ1) and the gamification elements (RQ3) (see Table 5), provides interesting information about domain-specific patterns of gamified digital twins. This analysis is performed according to the Game Elements Hierarchy by Werbach & Hunter in [7].

Across domains, the use of *Dynamics* reveals clear differences in how digital twins and gamification are conceptually framed. The *Dynamics*' element *Progression* appears consistently across all DT applications for the *Education* domain where it is used to guide learning paths according to task difficulty. Some educational systems also incorporate *Narrative* elements, and two include *Relationships* to support collaboration, particularly in team-based activities. In the *Industry/Manufacturing* domain, *Dynamics* are consistently centered around *Progression*, often enriched with *Narrative*, while *Emotions* supports engagement in only one paper. In *Healthcare*, the leading *Dynamics* are *Narrative*, *Progression*, and *Emotions*. These systems often rely on emotionally engaging scenarios or clinical storytelling to promote skill acquisition or therapeutic motivation. The *Cultural heritage* application domain is characterized by *Narrative* coupled with *Progression* and, in one case, also with *Emotions*. None of these systems activates social or relational dynamics, focusing instead on individual engagement. *Smart cities* and *Urban planning* applications show a strong emphasis on *Narrative* combined with *Relationships*. These domains leverage storytelling to contextualize socio-technical systems while, specifically in the *Urban planning* domain, *Relationships* element fosters citizen participation, collaborative planning, or collective decision-making. The DTs in the *Smart City* domain also exploit *Progression*. Finally, in the only paper framed in the *Environment* domain, there is a combination of *Narrative* and *Relationships* supporting citizens' participation in using a DT as a collaborative tool to foster environmental awareness and data collection.

Examining *Mechanics* across domains reveals how different sectors implement gamification elements to support user action and engagement. In *Education*, the most recurrent *Mechanics* are *Challenges* and *Feedback*, with few papers describing the use of *Rewards* and *Leaderboards* elements. *Education*-oriented DTs rely on challenges to structure a progressive learning path, with some systems incorporating *Competition* or *Cooperation* to support social learning dynamics. In *Industry/Manufacturing*, *Challenges* and *Feedback* are central. Some systems also include *Competition* or *Cooperation* for performance optimization and collaborative decision-making objectives. All DTs for the *Healthcare* domain rely on *Challenges* and *Feedback* elements. These systems replicate clinical contexts where immediate feedback is essential to performance correction and learning under pressure. The two papers framed in *Cultural heritage* present *Mechanics* gamification elements that promote motivation and enhance exploration: *Challenges* and *Rewards*. *Competition* and *Feedback* are also present, but not at the same time. DTs for the *Smart cities* domain incorporate *Feedback* together with *Challenges*, in one case, and with *Competition* and *Collections* in the other. These gamified DTs aim to motivate user participation and community engagement. The *Urban planning* domain relies on *Cooperation*; in one case, *Rewards* are also used, linking participatory design with strategies for incentivizing engagement. The only paper in the *Environment* domain relies solely on *Challenges* and *Cooperation*, reflecting the importance of citizen participation for environmental monitoring, promoting collaboration over competition.

Components highlight the concrete gamification tools used within each domain, revealing differences across sectors. *Educational* DTs clearly rely on elements aimed at making learning progress visible, creating milestones, or setting time constraints. In fact, the most recurrent *Components* are *Points*, *Leaderboards*, *Badges*, and *Progression bars*, followed by *Quests*, *Teams*, *Avatars*, and *Time constraints*. DTs for the *Industry/Manufacturing* field are mainly based on *Points*, with the integration of *Badges*, *Achievements*, *Leaderboards*, *Progression bars*, and *Levels*. This combination of *Components* reflects the need for monitoring performance, tracking operational progress, and promoting skills and efficiency. In the *Healthcare* application domains, all DTs include *Points*, in combination with *Leaderboards* and *Time Constraints*, or with *Progression bars* and *Avatars*, or with just *Achievements*. These elements are meant to reinforce performance and urgency in medical tasks. To favor the narrative nature of DTs in the field of *Cultural heritage*, the used *Components* include *Achievements* and *Leaderboards*. In *Smart cities* and *Urban planning* domains, the adopted *Components* include *Progression bars*, *Teams*, and *Quests*, mainly used to support citizen participation and collaborative problem-solving. Finally, in the *Environment*-based paper, the use of *Teams* is emphasized, highlighting the collaborative nature of citizen science.

A third cross-RQ analysis between application domains (RQ1) and the use of real-time data synchronization in digital twins (RQ2) provides insights into the way the design of DTs changes across different fields. The chart in Fig. 6 represents the number of papers that report the design of digital twins based on real-time data streams coming from their physical counterparts (green-colored bars) versus those papers that present DTs that are mainly relying on simulated data (red-colored bars), clustering them by application domain.

In only 7 out of the 23 included papers, the DTs are designed to work as updated system mirrors, thanks to the real-time data synchronization between the physical and the digital twins. Most of the papers belonging to the *Education* domain, i.e., the largest group in this study, do not present a DT that provides real-time data synchronization. This suggests that the educational process is built on simulation more than on real-time data and sensors. In *Cultural heritage*, *Urban planning*, and *Environment* domains, none of the described DTs rely on live data streams. In the first case, this is because real-time updates are not required, while in the second and third cases, the focus is more on supporting participation engagement than representing data through live sensing. *Smart cities* is the only domain where the

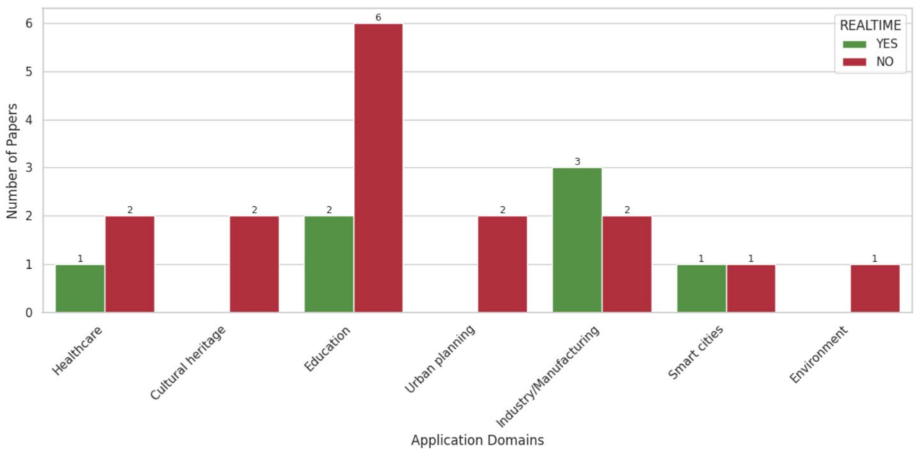

Fig. 6 For each application domain, this chart shows the number of papers that present digital twins relying on real-time data streams originating from their physical counterparts (REALTIME = YES) and those that are based on simulated data (REALTIME = NO)

two categories of DTs are equally represented. While the outcomes reveal some patterns and suggest that in different domains there is a tendency to design DTs in different ways, depending on how data are collected, the small difference between the numbers (apart from the Education field) prevents us from generalization.

5 Discussion

5.1 Findings and open issues

The analysis of the 23 papers included in this study enabled us to answer six research questions across several dimensions. The results reveal a research landscape that is still developing.

Education results as the most represented application domain of gamified digital twins. Gamification is exploited to foster the engagement of students or professionals in using the DT and thus better achieve SDG 4 (Quality education). Two other important domains where sustainability plays a crucial role are smart cities and urban planning: in both cases, citizens are encouraged to participate in shaping their urban environment or sharing important data for monitoring and decision-making at the city or neighborhood level, fostering the achievement of SDG11 (Sustainable cities and communities). Finally, SDG 9 (Industry, innovation and infrastructure) is achieved in all those projects that consider the implementation of DTs in the industrial manufacturing domain, where gamification can contribute to letting workers and employees not only learn how to operate machines at their own pace, but also to make them more motivated to work.

It emerged that SDGs 1 (No poverty), 5 (Gender equality), and 15 (Life on land) are not considered by any of the selected papers, and that some SDGs – e.g., SDGs 2 (Zero hunger), 6 (Clean water and sanitation), 7 (Affordable and clean energy), and 14 (Life below water) – are only marginally addressed. Therefore, there is a wide space for new research directions that integrate digital twin and gamification technologies to achieve such SDGs. It is also worth noting that most of the included papers present sustainability as a goal (e.g., energy efficiency, citizen engagement, environmental awareness), while only some works include sustainability objectives into the concept of DT itself, through optimization of resources, monitoring of key indicators, or feedback to users that shows the quantified impact of their decisions. A further limitation of the current research landscape concerns the lack of measurable sustainability outcomes. In most of the reviewed studies, sustainability is addressed through conceptual alignment with SDGs rather than through quantitative indicators (metrics) or empirically validated evaluation frameworks. Future work should therefore focus on developing sustainability objectives as measurable requirements, rather than as narrow motivations.

Current systems that integrate DTs and gamification only partially exploit the potential of designing with a human-centered approach and taking into account the most suitable multimedia interaction models for the prospective users. Very often, applications adopt immersive 3D or MR technologies, but rarely articulate how these modalities support users and whether they are the better solution for enabling them to reach their goals. Similarly, issues related to information overload, transparency, or controllability are usually not discussed in the papers. This lack of explicit reflection on interaction models reinforces the idea that multimedia design choices are frequently technology-driven, rather than systematically grounded in HCI.

Furthermore, real-time data synchronization is not always implemented; DTs are often used for simulation only, thus limiting the potential of DTs. Fully developed DTs can provide users with monitoring, prediction, data exploration, controllability, and adaptability features.

Regarding the immersive experiences often proposed in the selected papers, it is essential to note that measures must be implemented to mitigate the risk of overwhelming users or causing sickness and fatigue due to the use of VR or MR devices. The trade-off between encouraging participation, fostering engagement, and limiting the consequences of technology intrusiveness should be studied and designed properly. A further open issue, not yet adequately addressed in the literature, is that only a minority of the selected papers present studies involving potential users, either in system design or evaluation.

5.2 Design implications and a conceptual framework

The findings and open issues presented above lead us to derive the following implications for advancing the design of systems that integrate digital twins and gamification and that are meant to foster sustainability:

- *Design implication for digital twins*. In designing a gamified DT, it must be explored if and how to integrate real-time data synchronization to support the users in the decision-making process and, therefore, enable them to build trust in the digital twins.
- *Design implication for Gamification*. On the one hand, it is fundamental to determine which interaction models can truly benefit users in a specific application domain, considering both usability and accessibility, and avoiding fatigue or discomfort. In this way, the users will enjoy the experience and will be interested in continuing to use the DT. On the other hand, the gamification elements to be implemented in the DT must be properly selected to ensure long-term user engagement.
- *Design implication for Sustainability*. There is a need to transition from DT-based systems that merely convey general sustainability intentions to an approach that explicitly integrates sustainability by design. Such an approach would enable gamified digital twins to promote forms of engagement that are not only motivating for the user but also aligned with long-term sustainable behaviors and informed decision-making.

These three design implications represent the three driving forces within a conceptual framework for the future design of gamified digital twins that promote sustainability. The framework (depicted in Fig. 7) brings together digital twins, gamification, and sustainability as core elements that must be designed for and with the potential users. In this view, the digital twin provides the force that enables *awareness*, allowing users to understand the results of their actions and anticipate their consequences; gamification acts as a force that sustains *long-term engagement* and supports meaningful interaction with the DT; and sustainability works as a force that provides *direction and purpose* toward broader SDG-related values rather than domain-specific sustainability goals alone.

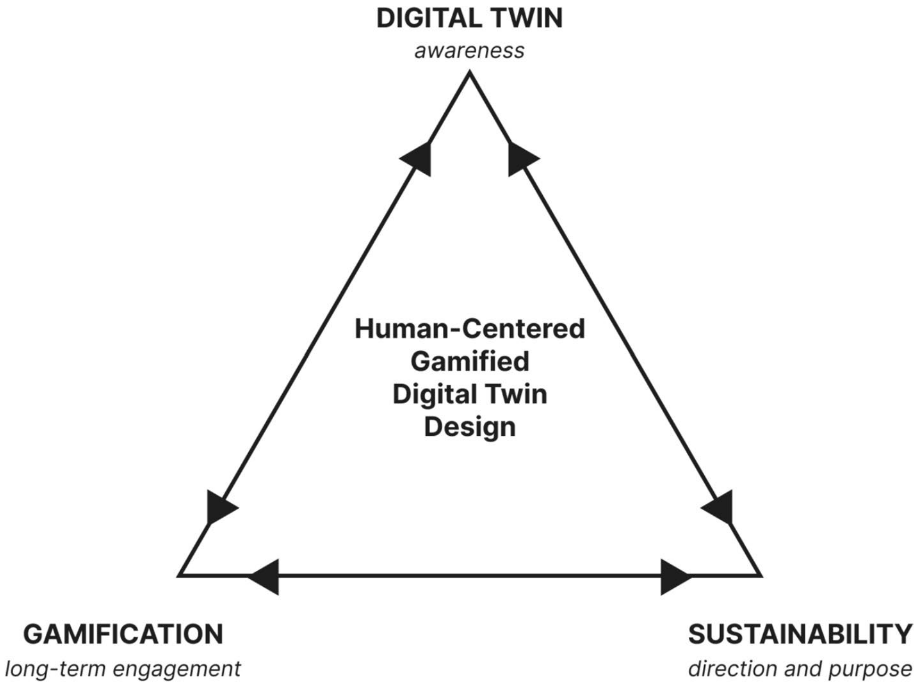

Fig. 7 The conceptual framework illustrates the three driving forces that should guide the design of gamified digital twins: *awareness* (enabled by the DT), *long-term engagement* (supported by gamification), and *direction and purpose* (driven by sustainability). Their interplay defines a human-centered design approach for gamified digital twins that promote sustainability

To illustrate more explicitly the contribution of the conceptual framework and clarify how it can be operationalized in concrete scenarios, we consider two of the representative application domains that emerged from this review: smart cities and education.

In a smart city scenario, a gamified digital twin would provide *awareness* by exposing citizens to representations of urban phenomena, such as mobility patterns, energy consumption, or environmental conditions, enabling them to understand the state of the city and the potential consequences of their actions or those of the broader community. Gamification would sustain *long-term engagement* by motivating continued participation through challenges, feedback, or collaborative activities that encourage citizens to interact with the system, and its users over time. Sustainability would provide *direction and purpose* by framing the use of the DT toward SDG-related values commonly associated with smart city initiatives, such as SDG 11 (Sustainable Cities and Communities) and SDG 9 (Industry, Innovation and Infrastructure), while at the same time opening the design space to address broader goals related to social inclusion, responsible resource use, and participatory governance – e.g., SDG 10 (Reduced Inequalities) and SDG 16 (Peace, Justice and Strong Institutions). In this way, user engagement would not be limited to domain-specific urban efficiency objectives but would also be oriented toward broader, long-term sustainability considerations.

In an educational scenario, a DT-based learning environment could apply the same framework by combining system transparency, progressive challenges, and sustainability-oriented framing. Here, the digital twin would support *awareness* by making learning processes, simulated systems, and cause–and–effect relationships explicit and understandable to students. Gamification would foster *long-term engagement* through structured progression and feedback that sustain motivation throughout the learning experience. Sustainability would provide *direction and purpose* by extending beyond SDG 4 (Quality Education), which is typically central in this domain. By framing learning activities within broader SDG-related values, such as responsible innovation, social awareness, and ethical decision-making, gamified digital twins could encourage students to reflect on the wider societal and environmental implications of their actions, supporting connections with SDGs beyond education alone – e.g., SDG 9 (Industry, Innovation and Infrastructure) and SDG 12 (Responsible Consumption and Production).

Unlike existing perspectives that address digital twins, gamification, or sustainability in isolation, this framework explicitly integrates these dimensions into a unified, human-centered design perspective for future gamified DT systems aimed at fostering sustainability.

Future research should also investigate further dimensions that still remain underexplored in the scientific literature. In particular, ethical considerations related to persuasive strategies implemented through gamification need further investigation. Especially when systems aim to influence human behaviour, there is a risk of behavioural manipulation. Moreover, as digital twins increasingly rely on real-time data streams, data governance, privacy, and responsible data use are critical and pose important challenges for their design. Among these concerns, there is the management of sensitive data retrieved in real-time through sensors and the potential biases in AI-driven DT systems that might affect the decision-making process.

5.3 Limitations of the work

The initial search query was very specific because we were interested in investigating the integration of DT and gamification technologies to foster sustainability. However, given the very small number of retrieved papers, we had to remove the word “sustainability” from the search string and work differently on this aspect (i.e., retrieving the metadata about SDGs when available and revising (or assigning) them iteratively to reach an agreement among the reviewers on the most pertinent SDGs for each paper). Despite this, the papers returned on the new search query were only 122, and most of them were not relevant or eligible for our literature review; thus, only 23 papers were finally included in the analysis. To compensate for this drawback, we conducted an in-depth analysis of each paper and confronted our opinions about how the papers addressed each dimension multiple times. However, it is worth noticing that there is no minimum acceptable number of studies in systematic literature reviews, nor does the PRISMA methodology provide any information about this aspect. On the other hand, this outcome can be regarded as a further contribution of this literature review, as it highlights an important gap in the considered research areas. We strongly believe that DT and gamification technologies can be effectively combined to design tools that foster the achievement of sustainable development goals.

Another limitation concerns the fast-paced evolution of this research area: as digital twin and gamification technologies continue to develop rapidly, this review should be interpreted as a snapshot of a rapidly changing research landscape.

6 Conclusion

This paper presents a systematic literature review on the integration of digital twin technologies and gamification in various application domains, examining their contributions to fostering sustainability. The study follows the PRISMA 2020 methodology and led to the selection and analysis of 23 scientific papers. The analysis of the papers was performed considering several dimensions to answer six research questions related to application domains, the use of real-time data synchronization, the most widespread gamification elements, interaction and visualization methods, user engagement, and the SDGs addressed.

The results show that education is the most explored domain, followed by industry and manufacturing, healthcare, smart cities, and urban planning. The integration of real-time data synchronization between the digital twin and its physical counterpart is only partially adopted, limiting the potential of DTs. User involvement in design and evaluation remains marginal. Finally, the most widely covered SDGs are SDG 4 (Quality education), SDG 9 (Industry, innovation, and infrastructure), and SDG 11 (Sustainable cities and communities), while others, such as SDG 1 (No poverty), SDG 5 (Gender equality), and SDG 15 (Life on land), remain unaddressed.

The discussion highlights the potential of integrating gamification into DT systems, which remains largely unexplored, and the reported case studies are often mere proofs of concept.

In summary, the review provides an overview of a still young research landscape, highlighting the results achieved so far and offering a set of design implications and a conceptual framework to guide the future design of gamified digital twins that foster sustainability.

Appendix A PRISMA items considered in the study

This appendix presents the correspondence between the sections of the article and the PRISMA 2020 items used in this study.

Table 7 PRISMA items included in this study, their brief description, and their position in this paper

Item	Description	Paper's section
1	Identify the report as a systematic review.	Title of the paper
2	Provide a structured summary including background, objectives, data sources, study eligibility criteria, participants, interventions, appraisal and synthesis methods, results, limitations, conclusions, and registration.	Abstract
4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	Introduction (Section 1) and Methodology (Section 3)
5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	Methodology (Section 3)
6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	Methodology (Section 3)
7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	Methodology (Section 3)
8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	Methodology (Section 3)
9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data, and details of automation tools.	Methodology (Section 3)
10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g., for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	Methodology (Section 3)
16a	Describe the results of the search and selection process, from the number of records identified to the number of studies included, ideally using a flow diagram.	Results (Section 4)
17	Cite each included study and present its characteristics.	Results (Section 4)
23a	Provide a general interpretation of the results in the context of other evidence.	Discussion (Section 5)
23b	Discuss any limitations of the evidence included in the review.	Discussion (Section 5)
23d	Discuss implications of the results for practice, policy, and future research.	Discussion (Section 5)

Author Contributions M.S., B.R.B., and D.F. conceived the idea of this study. M.S. performed the search of the papers on Scopus and prepared the shared spreadsheet. M.S., B.R.B., and D.F. contributed equally to the Identification, Screening and Analysis phases. M.S., B.R.B., and D.F. equally contributed to the manuscript preparation.

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Data Availability Data sets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Competing Interests The authors have no competing interests to declare that are relevant to the content of this article.

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