



Thermal, acoustic, and fire performance characterization of textile face mask waste for use as low-cost building insulation material

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ABSTRACT

Environmental issues are becoming increasingly important, and researchers are developing new technologies and models to reduce environmental impact. The circular economy is a production and consumption model that involves sharing, borrowing, reusing, repairing, reconditioning and recycling existing materials and products for as long as possible. This study focuses on the concept of reuse and, specifically, how to reduce waste generated by pandemics through recycling and reusing facemasks made of polyamide fabric. Facemasks can be reused to refurbish buildings in low-income contexts. To assess the reutilization potential of recycled bulk polyamide fiber, thermal, acoustic, and fire performance properties were assessed experimentally. The results show that they are comparable to commercial insulation materials such as glass wool and mineral wool in terms of thermal conductivity, while also demonstrating good sound absorption performance at medium and high frequencies (greater thickness and density will increase the amount of insulation and sound absorption). The material's fire performance is similar to that of other synthetic insulation materials, such as EPS. However, the performance is worse than for common organic insulation materials, such as cellulose. Finally, a low-cost, self-portable insulation panel concept designed for indoor installation was tested for material performance. Considering these properties, this solution may represent a significant opportunity to enhance thermal and acoustic comfort in vulnerable energy-poor households, bringing clear environmental benefits and positive social implications.

1. Introduction

In the European Union (EU), the building stock is responsible for 40% of final energy consumption and causes 36% of greenhouse gas emissions (Etzebarria-Mallea et al., 2021; Fernandez-Luzuriaga et al., 2021), making it a strategically important sector within the ambitious 2050 European energy policy (Passer et al., 2016). In particular, the EU residential sector consumes about 57% of the total final energy used for space-heating purposes (Chwieduk, 2003).

In the context of a global energy crisis, energy poverty, understood as a household's inability to secure a socially- and materially-required level of energy services (Bouzarovski, 2014), is becoming an increasingly significant problem in the urban contexts of southern Europe. Despite mild winters, the historic districts in many southern European cities are often home to low-income households in old, non-winterized buildings with low thermal efficiency. This population usually struggles to meet their energy needs for thermal comfort (Castaño-Rosa et al., 2020), suffering an increased risk of developing cold-related illnesses (Liddell

and Morris, 2010) or mortality (Healy, 2003). As one example, while 9.0% of the EU population was unable to keep their home adequately warm during the winter of 2016, this percentage was 13.4% among the Spanish population (Oliveras et al., 2021).

In Portugal, Spain and Greece, approximately 70% of the building stock was built during the 1960–1980s (Castaño-Rosa et al., 2020; Semprini et al., 2017), and building renewal rates are low. For instance, according to (Etzebarria-Mallea et al., 2021), in Spain only 0.8% of residential buildings were thoroughly renovated during 2014, compared to 1.82% in Austria, 1.75% in France or 1.49% in Germany. At these renewal rates, building retrofitting should be considered a long-term solution to the energy poverty issue. In the meantime, however, low-cost solutions are needed to also provide affordable thermal comfort to the most vulnerable population.

The EU wishes to move from a linear to a circular economy model, defined as a production and consumption model that involves sharing, lending, reusing, repairing, reconditioning and recycling existing materials and products (European Parliament, 2015). Once a product has

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Fig. 1. Polyamide-66 fabric face masks provided by Universitat Politècnica de Catalunya (UPC) to staff and students during 2021.

completed its function and reached its end-of-life, its components are put back into the production cycle wherever possible to extend its life cycle and minimize waste. Sustainable practices are increasingly important as society becomes aware of the environmental costs associated with current consumption models and production levels.

In recent years, several studies have examined the possibility of reusing a variety of bio-based or industrial waste materials as thermal and acoustic insulation, including sheep's wool, jute, recycled cotton, synthetic fabrics (e.g. polyester/polypropylene), cellulose, date palm wood or hemp, among others (Tran Le et al., 2010; Agoudjil et al., 2011; Zhou et al., 2010; Schiavoni et al., 2016; Aly et al., 2021; Abu-Jdayil et al., 2021; Ghermezzoli et al., 2021; Karimi et al., 2022; Dönmez and Turker, 2021). Other studies focused on the possibility of directly reusing End-of-life Household Materials (EoLHM)—such as cardboard panels, egg-boxes and clothes—in low-cost insulation panels with good acoustic and thermal performance (Neri et al., 2021a, 2021b; Neri, 2022). Therefore, affordable thermal and acoustic insulation solutions can be provided to EP-vulnerable populations by using EoLHM, defined as household waste that maintains exploitable properties, making it suitable for reuse despite reaching the end of its intended life cycle (Neri et al., 2021c). Among these household materials, synthetic fabrics represent a sizable portion of textile waste, but some of those materials, such as polyester, are not usually included in the recycling circuit (Bourguiba et al., 2020).

Since the COVID-19 outbreak, the production, use and discarding of personal protective equipment (PPE) such as facemasks has experienced a sharp upturn. Approximately 130 billion masks were thrown away every month during the early months of the pandemic (Prata et al., 2020; de Sousa, 2021). Managing this waste has become an enormous environmental problem (Saberian et al., 2021) since improper disposal can end up disrupting and damaging ecosystems and endangering wildlife (Prata et al., 2020; Fadare and Okoffo, 2020; Arduoso et al., 2021). Among the various types of facemasks, KN95 and cloth masks (Fig. 1) are some of the most used. Studies have proven that, although not as efficient as a KN95 mask, cloth masks could still provide users with a good level of protection against the virus (Beesoon et al., 2020), and therefore became a popular choice especially when medical-grade masks were unavailable. Cloth masks are usually made of several layers of polyamide-66 fabric, which is the material studied in this paper.

This scenario raises one clear question: how can cloth masks be transformed from waste to raw material, thereby reducing their environmental impact and discouraging their disposal? To answer this question, the research presented in this paper explores a way of reducing pandemic-generated waste by recycling and reusing polyamide-66 fabric facemasks as low-cost building insulation, aiming to enhance thermal

and acoustic comfort in vulnerable households, with clear environmental benefits and positive social implications.

For the purpose of this research, recycled polyamide-66 fiber (used to manufacture cloth facemasks) was studied as an insulation material with acoustic and thermal properties. The material's bulk acoustic, thermal and ignition properties were measured to assess its potential for reuse. The material performance was also tested in a low-cost constructive solution consisting of compact, self-portable insulation panels intended to be installed indoors.

The experimental tests developed to assess the recycled polyamide-66 insulation performance were carried out in various European laboratories. The thermal conductivity of the material was measured at the Ricert Laboratory in Vicenza (Italy), while the thermal performance of the low-cost construction solution was assessed at the Centre for Industrial Diagnostics and Fluid Dynamics (CDIF-UPC) in Barcelona, Spain. Acoustics experiments were performed at the Laboratory of Applied Acoustics at the University of Brescia, and at the National Research Council (CNR) in Milan, Italy. Fire performance, concerning both the recycled material and the construction solution, was assessed at the Materials Laboratory of the Barcelona School of Building Construction (EPSEB-UPC). Given the novelty of the research, this paper compared the aforementioned properties against those of other commercial insulation materials.

2. Recycled polyamide textile bulk properties

2.1. Thermal properties

The equivalent thermal conductivity (λ_{eq}) of the recycled polyamide-66 fiber was measured using the hot plate method according to UNI EN 12667:2002 standard (Ente Italiano di Normazione, 2002). For these tests, panels measuring $50 \times 50 \times 7$ cm were built using a 4 mm thin cardboard case (Fig. 2), which was filled with recycled polyamide-66 fiber. Bulk densities of 25, 30, 40, 50, and 60 kg/m³ were tested, as these are common density values for commercial insulating materials (Reif et al., 2016; Rockwool India, 2013). After a mechanical shredding process, the recycled fiber required for each case study was weighed and manually compacted inside the cardboard panel. Since the panel outer case is very thin, its thermal effects were considered negligible.

The panels were tested on a Lambda Meter EP500 apparatus manufactured by Lambda Messtechnik GmbH Dresden (Lambda-Messtechnik GmbH Dresden, 2023) according to EN 1946-2:1999 (Standards, 1999). In the apparatus, the samples to be tested were placed between a heating

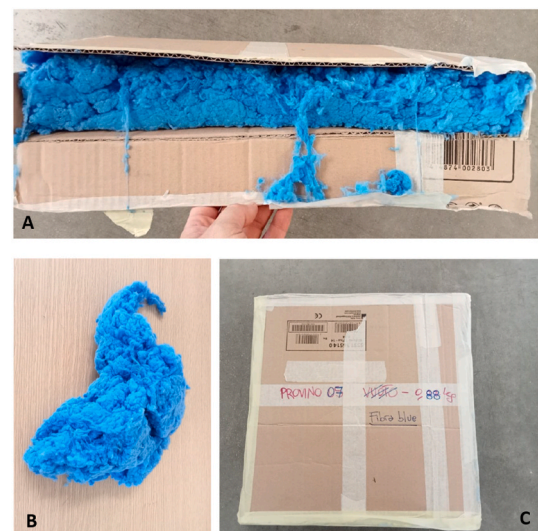


Fig. 2. Detailed view of the samples manufactured for the thermal tests. (A) Panel core. (B) Panel filling. (C) Finished panel.

element and a cooling element, ensuring one-dimensional heat flow through the test specimen. By measuring the power (q) supplied by the hot element, and the temperature difference (ΔT) between the sample surfaces, the equivalent thermal conductivity is determined as:

$$\lambda_{eq} = \frac{q \cdot s}{A \cdot \Delta T} \quad [\text{Eq. 1}]$$

Where A is the area of the heating element and s is the thickness of the sample. The tests were carried out in a conditioned chamber at $23 \pm 2^\circ\text{C}$ and $50 \pm 5\%$ relative humidity. The variation of the thermal conductivity parameter in the stable section of the test was lower than 1% for 220 min.

Fig. 3 shows the measured equivalent thermal conductivity (λ_{eq}) of the recycled polyamide-66 fiber at different bulk densities. All the measured values are lower than $0.04 \text{ W/m}\cdot\text{K}$, making its thermal conductivity comparable to other insulation materials. Fig. 4 compares the thermal conductivity of the recycled polyamide-66 fiber with that of other wastes and recycled materials (Tallini and Cedola, 2018), and with commercial insulation materials (Fortlan-Dibi, 2022). A mean value has been chosen when there was a range of values available. For polyamide-66, the mean value of the experimental results shown in Fig. 3 is reported. This demonstrates that polyamide-66 shows lower

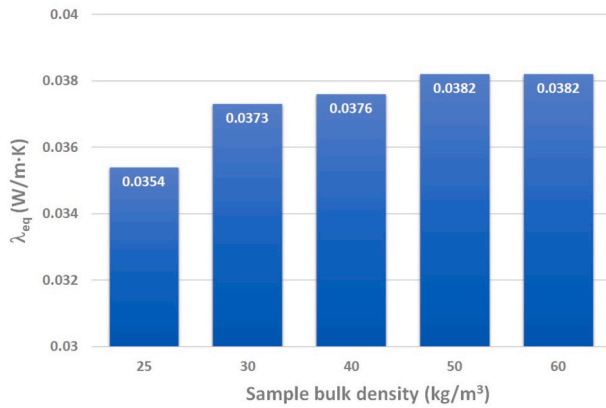


Fig. 3. Equivalent thermal conductivity of the recycled polyamide fiber at different bulk densities.

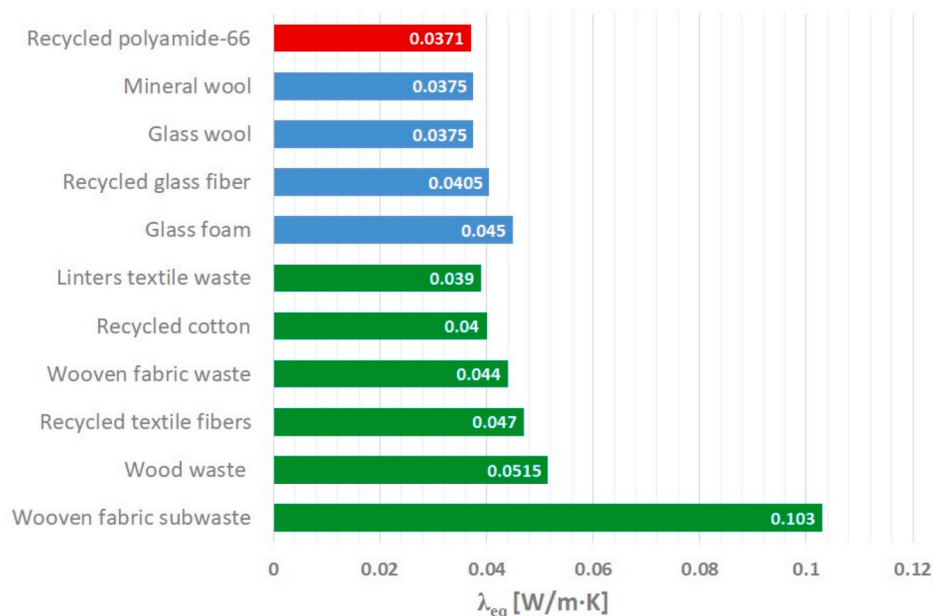


Fig. 4. Thermal conductivities for recycled polyamide-66 vs. other recycled (Tallini and Cedola, 2018) and commercial (Fortlan-Dibi, 2022) insulation materials.

thermal conductivity than many of the recycled materials listed, comparable to commercial insulating materials such as mineral and glass wools.

2.2. Acoustic properties

In building acoustics, the sound absorption and insulation of building materials and construction elements must be evaluated to ensure indoor comfort. High sound absorption coefficients reduce the consequent echo effect due to sound reflection on surfaces. Sound insulation is essential to separate neighboring spaces acoustically, reduce annoyance and provide privacy.

The impedance tube technique (which evaluates the material's acoustic performance when impinged by normal sound waves) was used to evaluate the acoustic performance of different samples of the recycled polyamide-66 fiber. The tests assessed the influence of the sample's thickness and density.

The sound absorption coefficient (α) and the sound transmission loss (TL) were measured for 10 samples of recycled polyamide fabric (Fig. 5A). Thicknesses of 50 and 100 mm were studied to assess influence on the bulk acoustic properties. Bulk densities of 25, 30, 40, 50, and 60 kg/m^3 were tested for each thickness. Samples were prepared following a similar procedure as described in section 2.1. To contain the material and ensure a flat surface (hypothesis on which the mathematical model is based), two glass tissue discs were fitted on both circular ends of the sample tube.

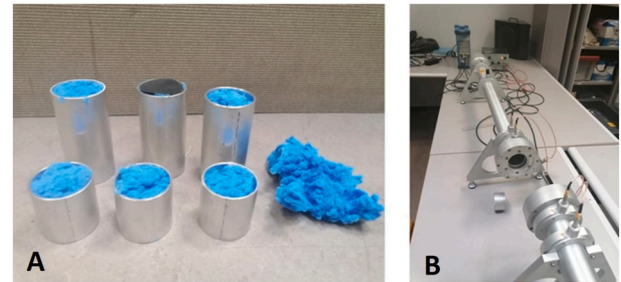


Fig. 5. Acoustic characterization of the textile waste. (A) Sample tubes filled with polyamide-66 fiber. (B) Impedance tube apparatus.

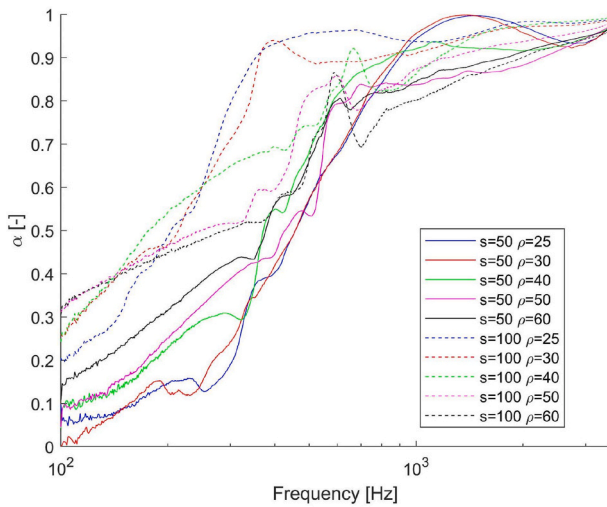


Fig. 6. Normal incident sound absorption coefficient (α) for the tested samples.

The impedance tube apparatus, shown in Fig. 5B, consisted of two tubes with a diameter of 4.6 cm, connected to a circular test sample holder (where the sample tube was inserted). Two microphones were placed along the tube, 45 mm apart on either side of the specimen. The test consisted of emitting pink noise at one end of the tube and receiving the transmitted and reflected signals using the microphone array at both ends of the sample. The pressure and velocity of the traveling and reflected waves were then calculated using a multi-channel Fast Fourier Transform (FFT) MATLAB script, implemented according to ASTM E2611-19 standard (ASTM International, 2019). Analyzed frequencies ranged from 100 to 3150 Hz. During the tests, room temperature and pressure were 27 °C and 99.58 kPa, respectively. Three tests were performed for each sample, and results were averaged arithmetically.

Fig. 6 shows the measured sound absorption coefficients. The data shows an S-shape trend, typical of porous materials, characterized by low absorption values at low frequencies and high values in the high-frequency range.

Results from samples with the same thickness were compared to assess the influence of the sample bulk density on the sound absorption coefficient. In general, lower-density samples show higher α values in the mid-range frequency range (0.5–2 kHz), hence demonstrating better acoustic performance. This is more visible when focusing on the results from 100 mm-thick samples. In this case, the lower density samples (25–30 kg/m³) out-perform all other samples both in the low to mid-range (0.25–0.5 kHz) and the mid-range frequency ranges, and the highest α values (of about 0.9) are attained by the lowest density sample in the 0.4–0.7 kHz frequency range. This is due to sound reflection on the surface of very dense materials, preventing the sound from entering the inner part of the material where it would be dissipated.

To assess the influence of sample thickness on the sound absorption coefficient, samples with the same density are compared. In general, it can be observed that some of the low-thickness samples show the highest α value for the 1–2 kHz frequency range, while the thicker samples show better overall performance across a wider frequency range. For example, for a bulk density of 25 kg/m³, on the thicker α sample reaches a value of about 0.4 at 0.2 kHz, and 0.9 at 0.5 and 1 kHz. For the 50 mm-thick sample, these values are about 0.1, 0.6 and 1.0 respectively. Based on these results, better sound absorption occurs for high-thickness/low-density samples. Since there are different sounds in the built environment, characterized by different frequencies, it is better to choose a material with medium-to-high sound absorption values in a wider range of frequencies, rather than a material that can absorb only specific frequencies.

The TL results are shown in Fig. 7. All samples show an initial flat trend followed by a reduction in TL due to structural resonance, and

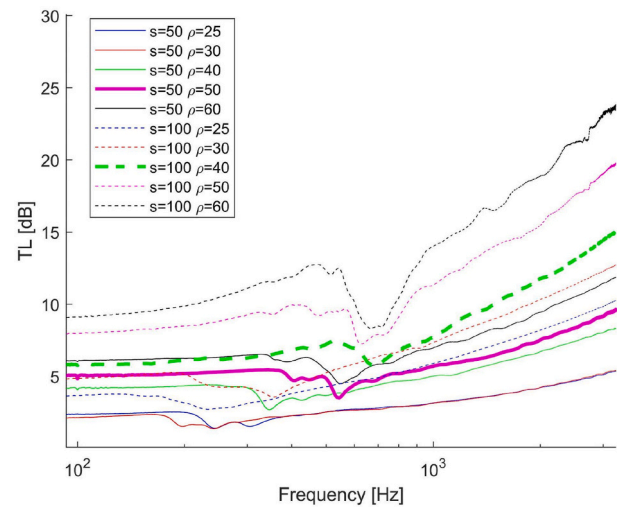


Fig. 7. Sound transmission loss (TL) for the tested samples.

then a rapid increase (greater at higher density values). For samples with the same density, the thicker ones show higher TL values hence better sound insulation performance. 100 mm-thick samples perform better across the entire frequency range, and it can be observed that density significantly affects sound insulation performance. For 50 mm-thick panels, the TL does not exceed 10 dB, while for 100 mm-thick samples it ranges between 5 and 24 dB depending on frequency and density. The best performance comes at high frequencies, while it is poor at low frequencies. Indeed, TL is governed by stiffness and rigidity at low frequency. Better performance is detected for higher-density panels since they show relatively higher flux resistivity, sound energy backward reflection, and a reduced portion of the transmitted sound energy.

By comparing the results obtained for α and TL, two opposite trends can be detected. A higher sound absorption coefficient was obtained for thicker, low-density samples, while higher sound-insulating performance was attained for thicker, high-density samples. Since low-density samples displayed lower thermal conductivities, it appears that to obtain a panel with both good thermal and acoustic performances, the recycled polyamide fiber must be coupled to other elements that would improve its performance in the low-medium frequency range, corresponding to noise from urban road traffic, factories, disco music, or jet aircrafts.

One parameter widely used to compare the sound absorption performance of materials is the Noise Reduction Coefficient (NRC), which is

Table 1

Noise reduction coefficients for recycled polyamide-66 vs. other construction and acoustic insulation materials from (Egan, 2007; Foreman, 1990).

Material	Sample characteristics		NRC
	Thickness (mm)	Density (kg/m ³)	
Glass fiber	70		0.95
	22.5	semi-rigid	0.63
Cellulose fiber sprayed on concrete	22.5	–	0.88
Recycled polyamide-66 fiber	100	25	0.86
		40	0.82
		60	0.71
	50	25	0.64
		40	0.71
		60	0.70
Mineral fiber	–	40–70	0.80
Bulk polyester	–	–	0.61
Perforated cardboard	–	–	0.42
Polyurethane foam	22.5	–	0.30
Plaster	–	–	0.15
Wood	–	–	0.10
Painted brick	–	–	0.10
Non-perforated cardboard	–	–	0.01

the mean value of the sound absorption at frequencies of 250, 500, 1000, and 2000 Hz. Table 1 compares NRC values calculated for the recycled polyamide fiber with values reported for other insulation materials commonly used in the construction sector (Egan, 2007; Foreman, 1990). Since the NRC obtained for the recycled polyamide fiber is quite large, it can be useful to apply this material to reduce sound reverberation in a confined atmosphere. However, the material cannot be installed without a casing that could modify the sound absorption performance.

2.3. Fire properties

Some fire properties of recycled polyamide-66 fiber were determined by means of pyrolysis-combustion flow calorimetry (PCFC) tests according to the ASTM D7309 standard (ASTM International, 2021), on an FAA micro calorimeter manufactured by Fire Testing Technology Limited (Fire Testing Technology Limited, 2022). This technique enables parameters such as the specific heat release rate (HRR) to be determined quickly from very small (1–5 mg) specimens.

The specimens tested in the PCFC micro calorimeter were initially heated at a constant temperature increase rate (typically 1 °C/s) in a pyrolyzer, and the degradation products were purged from it by an inert gas (nitrogen). The gas stream was then mixed with an oxygen stream before entering a combustor at 900 °C, where the degradation products were completely oxidized. Oxygen concentrations and flow rates of the combustion gasses were used to determine the oxygen consumption involved in the combustion process and the HRR were determined from these measurements.

Fig. 8 shows the results obtained for HRR vs. combustion temperature for the recycled polyamide fiber (test sample). Three other commercially-available insulation materials were also tested for comparison purposes: extruded polystyrene (EPS), cellulose and corn pith. As shown, the recycled polyamide fiber and EPS have similar performance, as both are synthetic polymeric products, with a large heat release peak at around 430 °C. In contrast, both natural insulation materials (cellulose and corn pith) show smaller heat release peaks, although at lower temperatures.

Other parameters related to the material's fire risk were estimated from the HRR data: the total combustion heat release (HR), which is the integral of the HRR curve over the test time, the ignition temperature (T_0), which is considered here as the temperature at which HRR reaches

Table 2

Fire risk parameters for recycled polyamide-66 fiber vs. other synthetic and natural insulation materials from (Palumbo et al., 2015).

Material	HR (MJ/kg)	T_0 (°C)	PHRR (W/g)	T_{max} (°C)
Recycled polyamide-66	26.1	379	684	430
EPS	39.7	343	813	436
XPS	38.7	339	631	434
Polyurethane	13.5	200	85.0	335
Cellulose	11.5	305	193	376
Corn pith	8.70	221	100	321
Barley straw + starch	7.10	229	68.4	313
Rice husk + alginate	5.80	250	58.0	335

10 W/g, the maximum specific heat release rate (PHRR) and its corresponding temperature (T_{max}). Table 2 shows the results obtained for the four insulation materials being tested. For comparison purposes, values for other natural and synthetic insulation materials have been added from (Palumbo et al., 2015). As shown, the fire behavior of the recycled polyamide fibers is closer to other synthetic materials rather than insulation with natural/organic origin. The recycled fibers demonstrate a lower fire risk than polystyrene foams due to the higher T_0 and lower HR meaning that the material burns faster with a lower total heat release. The maximum specific heat release rate occurs at a temperature comparable to that of polystyrene foams. Other typical insulation materials, such as mineral wool or glass wool, are not included in this table because they are non-combustible products.

3. Characterization of the insulating construction solution

The second part of the study assessed the acoustic, thermal, and fire performance of the recycled polyamide fiber (alone or in combination with other EoLHM) in construction solutions intended for low-income households.

3.1. Thermal performance

For the thermal performance tests, a construction solution was manufactured consisting of a self-portable cladding panel made of a 10 mm medium-density fiberboard (MDF) plaque mounted on a 40 × 40 mm pinewood frame, as shown in Fig. 9A. This solution was chosen due

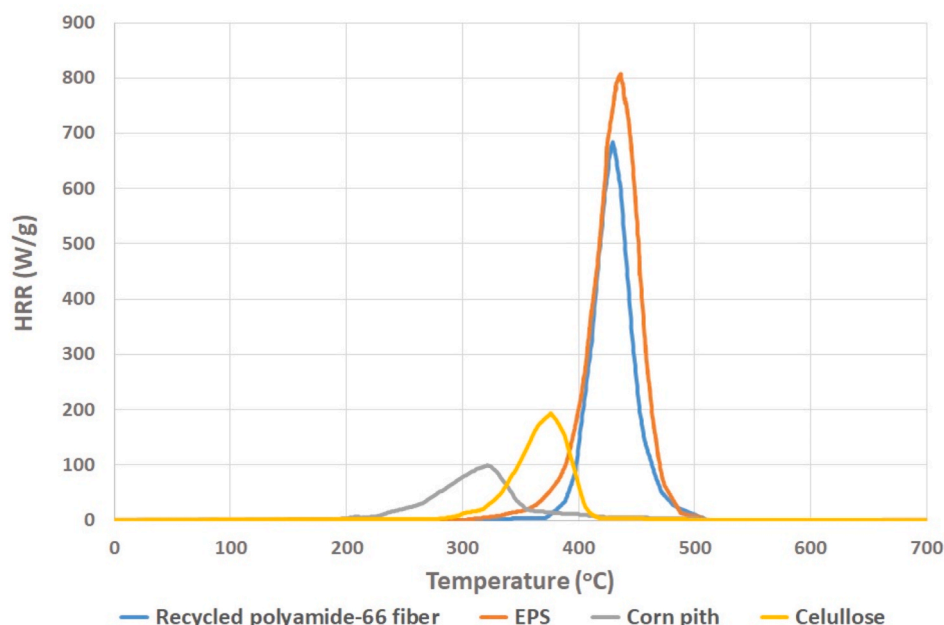


Fig. 8. HRR for insulation material samples of different origins.

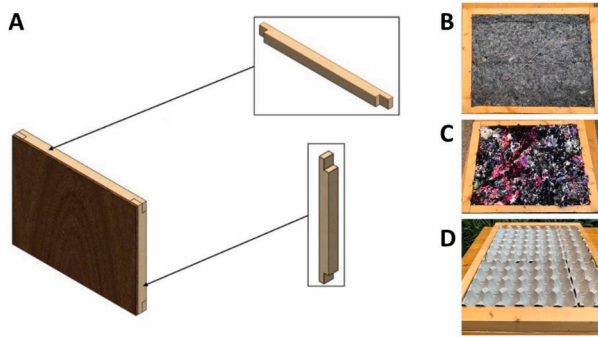


Fig. 9. Self-portable cladding panel used in the thermal performance tests. (A) Construction detail. Insulation materials: (B) recycled cotton. (C) Recycled polyamide. (D) Recycled polyamide + egg cartons.

Table 3
Prototype samples tested.

Prototype sample	1	2	3	4	5	6
Insulation material	Recycled cotton (commercial)	Recycled polyamide-66 fiber		Recycled polyamide-66 fiber + egg cartons		
Insulation bulk density (kg/m^3)	40	25	40	60	25	40

to its low cost and overall easy manufacturing and installation: being portable, the cladding can be pre-fabricated off-site, and its installation does not require construction work or qualified labor, which makes it suitable for application in low-income households.

The cladding cavity (40 mm thick) was then filled with an insulating material. The recycled polyamide fiber thermal performance in the constructive solution was tested for various insulation bulk densities. Its performance was also tested in conjunction with egg cartons. A sample using a commercially-available recycled cotton thermal insulation was also tested for comparison. Table 3 shows the six insulation configurations which were tested and Fig. 9B, C and 9D show the cladding cavity with the insulation materials used.

A calibrated hot box (Lu and Memari, 2018) with a 600×455 mm

test section was used to test the thermal performance of the specimens. The heat flux through the cladding prototype was measured using a HukseFlux HFP01 heat flux sensor and a LI19 data logger. The surface temperatures on both sides of the samples were recorded using K-type thermocouples connected to an Extech Instruments SD2000 temperature data logger. The accuracy was ± 0.1 °C for the temperature sensor and $\pm 5\%$ for the heat flux sensor. The room temperature was kept at 23 ± 1 °C throughout the experiments. Recorded data was used to determine the thermal resistance (R_T) of the self-portable cladding solution. Data was collected for at least 3 h after the experimental setup attained steady conditions. Fig. 10 shows the results obtained for the configurations being studied.

The results show that the recycled polyamide fiber demonstrates better thermal performance than the recycled cotton insulation, reaching similar thermal resistance values with lower insulation bulk densities. Moreover, adding egg cartons to the insulation filling increases the thermal resistance of the cladding by about 10%, probably because of the air chamber formed between the egg cartons and the back cover of the cladding.

3.2. Acoustic performance

In this part of the study, the sound insulation performance was tested on a panel consisting of recycled polyamide fiber, egg cartons and cardboard elements, determining the sound transmission loss (TL) and the sound reduction index (R_w). The panel measured $1 \times 1.2 \times 0.07$ m, with a surface density of 4.36 kg/m^2 (Fig. 11). To build the panel, the egg cartons were glued onto a cardboard panel, and five holes were drilled in each egg carton dome. The cardboard elements were 4 mm thick and consisted of two external liners and a fluted core. The egg boxes were made of a 2 mm paper layer, and the total thickness of the box was 6 cm. The egg cartons were filled with recycled polyamide fiber with a bulk density of 12.5 kg/m^3 . The external case was then completed using cardboard elements side-by-side connected with adhesive tape. Finally, one of the external cardboard surfaces was drilled with 1420 holes, 2.9 mm in diameter.

The test was performed in a sound transmission room, schematized in Fig. 12. The room consisted of two acoustically-decoupled spaces separated by a wall in which the sample to be tested was installed: one room was called the 'source room' and the other the 'receiving room'. The source room had a volume of 50 m^3 and a total surface area of 79.5

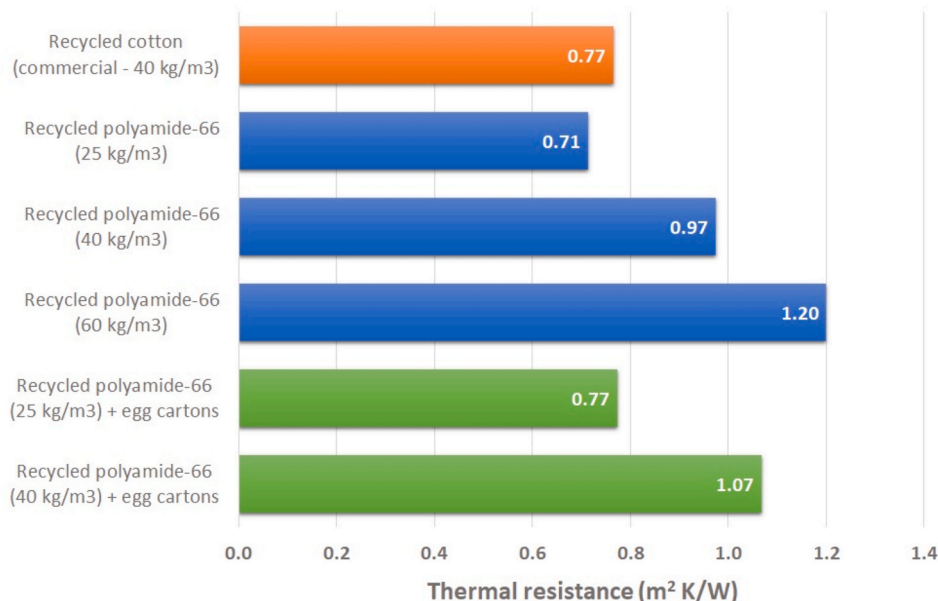


Fig. 10. Thermal resistance of the studied configurations.



Fig. 11. Detailed view of the constructed panel and its setup at CNR sound transmission room. (A) Specimen installed in the sound transmission room. (B) Panel external surface. (C) Insulating core. (D) Example of the holes drilled on the external case. (E) Drilled egg carton domes.

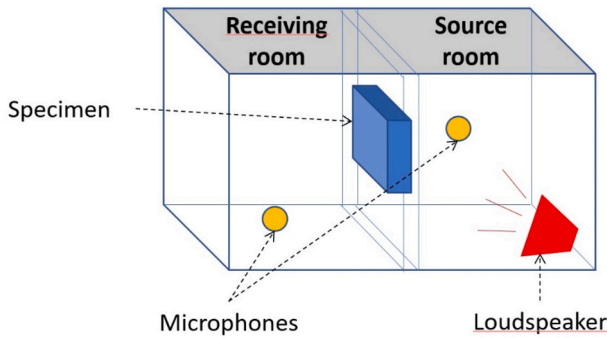


Fig. 12. Scheme of the sound transmission room.

m², while the receiving room was 60 m³ and 91.5 m² respectively. The panel was fixed to the test area using four wooden laths 15 × 15 mm in dimensions, and crevices were sealed using silicone as shown in Fig. 11B.

The TL measurement test consisted of generating a diffuse sound field in the source room by activating an omnidirectional loudspeaker, while the average sound pressure level (L_p) in both the source and the receiving rooms was measured by using a continuously-moving microphone. Measurements were made by using a 1/3-octave filter and in frequencies from 0.1 to 5 kHz. The room temperature, humidity and pressure during the test were 29.5 °C, 53.7%, and 100.41 kPa respectively.

Defining T_m as the measurement time duration, L_p is calculated according to ISO 10140-2 (International Organization for Standardization, 2010) standard:

$$L_p = 10 \cdot \left(\frac{1}{T_m} \right) \int_0^{T_m} \frac{p^2(t) dt}{p_0^2} \quad [\text{Eq. 2}]$$

Where T_m is the integration time, p is the sound pressure and p_0 is the reference sound pressure (equal to 20 μPa). TL is then calculated as:

$$TL = L_{p1} - L_{p2} + 10 \log \left(\frac{S}{A_a} \right) \quad [\text{Eq. 3}]$$

Where L_{p1} and L_{p2} are the average sound pressure levels in the emitting and the receiving rooms respectively, S is the sample area, and A_a is the equivalent sound absorption area of the receiving room calculated according to (International Organization for Standardization, 2010):

$$A_a = 0,16 \frac{V}{TR} \quad [\text{Eq. 4}]$$

Where V is the volume of the receiving room and TR the reverberation time.

According to Fig. 13, the sound transmission loss is higher than 7 dB in the entire frequency range. The panel shows weak performance at low

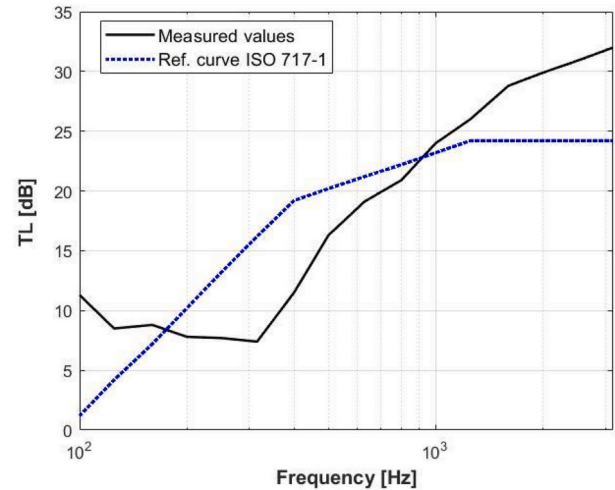


Fig. 13. Sound transmission loss measured, compared to the reference curve defined in the ISO 717-1 (International Organization for Standardization, 2020) standard.

frequencies since it is made of light materials and in this frequency region, the performance is strongly influenced by the mass per unit area of the element. Up to 315 Hz, the transmission loss decreases due to the panel resonance caused by mass-spring-mass system behavior, but from there up to 1.6 kHz, TL increases with frequency: 12 dB per octave between 315 and 630 Hz and 9 dB per octave between 630 and 1600 Hz. Between 1600 and 3150 Hz the curve decreases at a rate of about 4 dB per octave. Although it is not possible to directly compare the results obtained for the bulk material in the impedance tube against results in the sound transmission room for the panel, for the panel, above 800 Hz TL is higher than 20 dB, and at 500 Hz it is 16.3 dB. Therefore, the panel can improve the acoustic condition when fitted indoors. However, the sound performance of the panel can be improved by optimizing the number and size of the holes, the characteristics of the external case and the core configuration.

For a more straightforward comparison of the acoustic performance of different materials, the measured sound transmission loss curve is corrected to a reference curve (defined by the ISO 717-1 (International Organization for Standardization, 2020) standard and shown in Fig. 13) to obtain a single numerical value known as the sound reduction index (R_w), which is then given by the transmission loss value obtained for the corrected reference curve at 500 Hz. As can be seen in Fig. 13, R_w is 20.2 dB for the analyzed panel. In this analysis, important information on low and high frequencies is lost. To overcome this problem, two other parameters C and C_t are introduced. The soundproofing power calculated by adding the C term to R_w refers to the behavior of the partition exposed to sound in the middle-high frequency. Noise in the middle-high frequency is the typical noise caused by conversation, television, medium- and high-speed rail traffic and highways with traffic speeds above 80



Fig. 14. Dripping test device.



Fig. 15. Cladding sample used in the fire performance tests.

km/h. The partition behavior at the medium-low frequencies is calculated by adding C_{tr} to R_w ; noise from urban road traffic, low-speed rail, airplanes, jet planes, disco music and factories falls within this range. For the analyzed panel, R_w is 20.2 dB and C and C_{tr} are 1.7 and 4.9 dB respectively.

3.3. Fire performance

The insulation construction solution shown in Fig. 9 was tested to evaluate its fire performance by means of a dripping test with electrical radiator, according to the UNE 23725:1990 (*Asociación Española de Normalización, 1990*) standard. The purpose of this test is to register the ignition time, in other words the moment when the first flames appear, their persistence once the heat source has been removed (hence, the self-extinction capacity of the tested material) and whether the material might drip once in flames.

The tests were carried out using a 745-745E dripping test device model, manufactured by Instruments J.Bot S.A (*Instruments and Bot, 2015*), shown in Fig. 14. The device consists of a frame to hold a sample (a stainless-steel adjustable ring and a metal grill), a container to collect resulting drops, and a rotating radiator that can either be placed above the sample, or removed to evaluate the self-extinction capacity of the

Table 5

Summary of the fire performance test results.

Sample	Ignition time (s)	Average ignition duration (s)	Number of ignitions	Total mass loss (%)	Ignited material dripping
Polyamide-66 on metal grid	46	153	7	93	Yes
Polyamide-66 on ceramic base	43	57	10	18	No
Recycled cotton on metal grid	46	160	7	44	Yes
Recycled cotton on ceramic base	47	49	12	20	No

tested material.

Fig. 15 shows an example of the samples used for the dripping test. Samples consisted of a $100 \times 100 \times 54$ mm frame made of 10 mm thick pine wood panels, covered on one side by a 3 mm-thick MDF panel, (which was exposed to the heat source). The box was then filled with the recycled textile insulation material, replicating at small scale the constructive solution presented in Section 3.1. The fire performance of the recycled polyamide-filled panels was compared to that of a panel filled with commercially-available recycled cotton insulation.

Two tests were set for each sample, following the same protocol in each case although changing the support on which the samples were placed. To determine the influence of how the constructive solution was applied to the wall (merely leaning on it or fixed by adding a sealing cover on its rear-side) on its fire performance, the sample was placed on a ceramic tile in one case, while it rested on top of a metal grid in the other. Table 4 shows the results obtained for tested samples in relation to their ignition time (moment when the material first ignites), their extinction time (moment when the fire is extinguished), and the duration of combustion (time ignition lasts for each one).

Table 5 shows the most significant results obtained for the different samples summarized as follows: the ignition time (time of the first flame occurrence), the average duration of flames (gives an idea of the self-extinguishing capacity of the material), the number of ignitions (indicates the amount of ignition that occurred during the first 5 min of the test), and the total mass loss at the end of the test.

As the fiberboard panel was exposed to the heat source, the behavior observed in Fig. 16 at the start of all the tests is its reaction to fire. The ignition time, plus the tendency to extinguish the flames in the first ignitions for the four samples, are typical of lignocellulosic materials such as wood.

Table 4

Constructive solution fire performance test results.

Flame occurrence	Polyamide-66 on metal grid			Polyamide-66 on ceramic base			Cotton on metal grid			Cotton on ceramic base		
	Ignition (s)	Extinction (s)	Duration (s)	Ignition (s)	Extinction (s)	Duration (s)	Ignition (s)	Extinction (s)	Duration (s)	Ignition (s)	Extinction (s)	Duration (s)
1	46	51	5	43	51	8	46	50	4	47	53	6
2	54	60	6	53	53	1	53	58	5	57	65	8
3	64	78	14	61	67	6	61	246	185	69	79	10
4	81	243	162	69	76	7	69	245	176	82	198	116
5	252	258	6	78	209	130	248	295	47	201	206	5
6	260	343	83	211	223	12	301	438	137	208	227	19
7	357	1150	793	225	257	32	451	1015	564	229	233	4
8				260	263	3				235	241	6
9				265	327	62				243	283	40
10				330	641	311				285	297	12
11										298	319	21
12										325	665	340

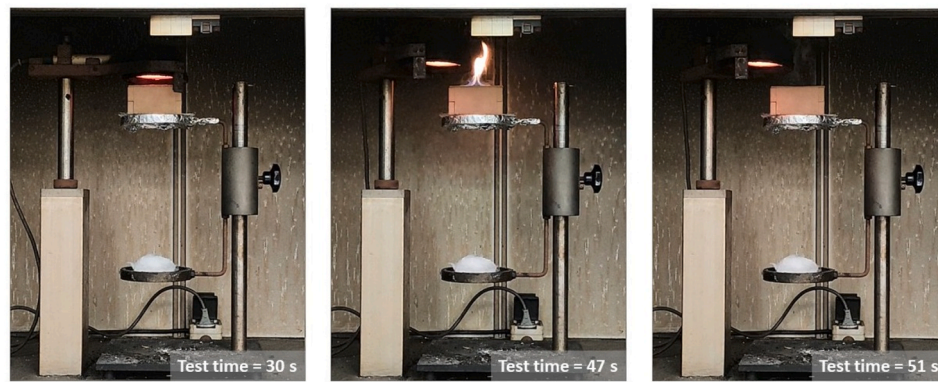


Fig. 16. Behavior of the polyamide-66 on metal grid sample at the beginning of the test. The ignition of the fiberboard panel and extinguishing of the flames are observed.



Fig. 17. Sample condition after the fire performance test for the polyamide on metal grid case.



Fig. 18. Dripping of ignited material for the polyamide on a metal drip case.

As the test progressed and the insulating material was affected by the heat, the persistence of the flames increased. Higher mass losses were recorded for the sample positioned on the metal grid, especially in the case of the recycled polyamide fiber, where the mass loss reached 93%

(Table 5). As shown in Fig. 17, the pinewood frame was almost completely burnt after the test. Ignition duration was about three times the values obtained for the samples resting on top of a ceramic tile support. During the test, the metal grid support allowed oxygen to flow towards the insulation core, and also allowed viscous material to drip out (Fig. 18). This dripping occurred about 2 min after applying constant heat to the sample piece filled with recycled polyamide fiber, and after about 5 min in the case of commercial cotton insulation. This behavior explains the differences in total mass loss recorded for these cases.

When the tested samples rested on ceramic tiles, the insulation material confinement plus the lack of oxygen in the insulation core made it difficult for them to burn. This occurred for both insulation materials tested, leading to comparable results for all the parameters measured (Table 5). However, the constructive system partially maintains its structure, helping to keep the insulation inside (Fig. 19). This reduces the mass loss by about 20% in both cases and prevents the inflamed material from dripping.

4. Conclusions

The study presented in this paper aims to explore the feasibility of repurposing cloth mask waste, minimizing its adverse impact on the environment and working towards a circular and sustainable economy. It assessed whether recycled polyamide-66 fiber, used in cloth facemask manufacturing, is suitable as cheap insulation material to improve the thermal and acoustic comfort in vulnerable households. The experimental campaign presented here provides direct information on the feasibility of the proposed approach. It particularly analyzed the thermal, acoustic and fire properties of the recycled fibers both as bulk material and as the insulation layer in a low-cost constructive solution.

The thermal conductivity of the recycled fiber is 0.037 W/m·K, comparable to popular commercial insulating materials such as mineral wools or glass wools. The sample's bulk density does not significantly affect its thermal performance, but it does affect its acoustic performance. The sound absorption coefficient and the transmission loss coefficient demonstrate good performance at medium and high frequencies, in accordance with the theory of porous materials. For the bulk material, better sound absorption was found to occur for thicker/lower density samples while higher sound insulating performance was attained among thicker, higher-density samples. The material's fire performance is similar to other synthetic insulation materials such as polystyrene foams, but poorer than natural/organic insulation material like cellulose or corn pith.

The second part of the study assessed the thermal, acoustic and fire performance of low-cost insulation panels filled with recycled polyamide-66 fiber (alone or in combination with other End-of-Life Household Materials).

From the thermal performance tests, it was noticed that the recycled

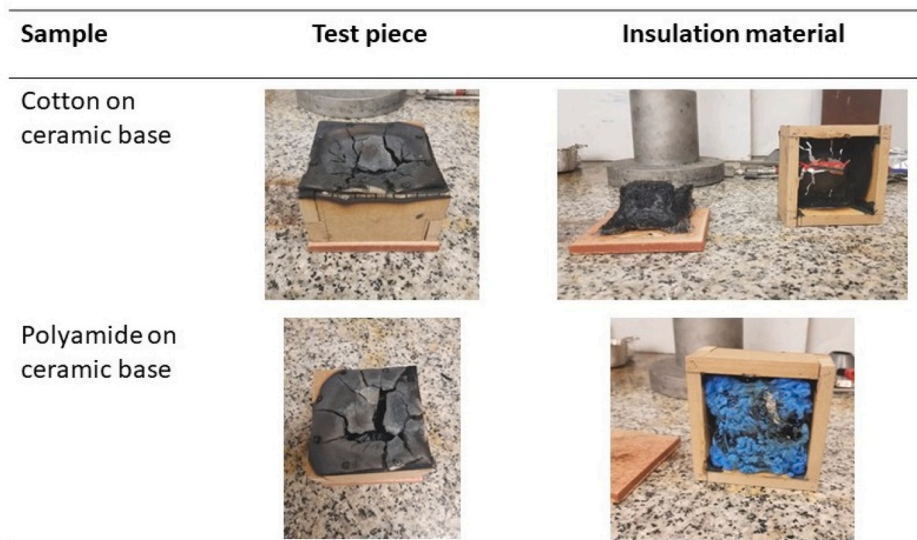


Fig. 19. Sample piece condition after the fire performance test.

polyamide fiber demonstrates better thermal performance than commercially-available recycled cotton insulation, achieving similar thermal resistance values with lower insulation bulk densities. Moreover, adding egg cartons to the insulation core increases the thermal resistance of the cladding by about 10%.

Acoustic test results show that the recycled polyamide-66 fiber + egg carton insulating panels demonstrate poor performance at low frequencies, probably due to the materials' low surface density. Up to 315 Hz, the transmission loss decreases due to panel resonance caused by mass-spring-mass system behavior, although from there up to 1.6 kHz, TL increases with frequency: 12 dB per octave between 315 and 630 Hz and 9 dB per octave between 630 and 1600 Hz. Although it is not possible to compare the results obtained for the bulk material and the insulating panel directly, it should be noted that for the panel, above 800 Hz TL is higher than 20 dB, and at 500 Hz it is 16.3 dB, values significantly higher than those obtained for the bulk material at similar frequencies. Therefore, the panel can improve the dwelling's acoustic comfort when fitted indoors.

Fire performance tests for the constructive solution show that for a wall-fixed application, a back-sealed insulating panel shows an acceptable reaction to fire, as it prevents the recycled polyamide-66 fibers from burning and the leaking of ignited material. However, in a non-sealed solution, the large oxygen supply to the insulation core creates potentially dangerous behavior, with a greater fire load and the appearance of ignited material dripping.

Considering the above, we can conclude that polyamide-66 facemask waste demonstrates good potential as a low-cost insulating material, and that its use in low-cost insulating indoor panels may represent a great opportunity to enhance thermal and acoustic comfort in vulnerable households, providing environmental benefits with positive social implications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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