Journal of Material Cycles and Waste Management
https://doi.org/10.1007/s10163-020-01024-3

ORIGINAL ARTICLE

Recycled leather cutting waste-based boards: thermal, acoustic, hygrothermal and ignitability properties

M. Barbanera[1] · E. Belloni[2] · C. Buratti[2] · G. Calabrò[1] · M. Marconi[1] · F. Merli[2] · I. Armentano[3]

Received: 19 December 2019 / Accepted: 19 March 2020

Abstract
This study investigates the possibility to reuse finished leather scraps, produced by the leather goods industry during the cutting phase, for the preparation of innovative panels for thermal-noise building insulation. Experimental panels were prepared by chipping the leather cuttings, using polyvinylacetate binder, and pressing the paste in a mold through a mechanical press. Boards were tested for thermal and acoustic performance, thermal stability, hygrothermal, wettability and ignitability properties. Acoustic measurements by means of a Kundt's tube, and thermal characterization by means of a small hot–box system were performed. The measured thermal conductivity was 0.104 W/(mK) and 0.108 W/(mK) for the 45 °C and 50 °C set-up hot temperatures, respectively. Concerning the acoustic performance, two panels with thickness of 18-mm and 28-mm were produced: they were characterized by a noise reduction coefficient of 0.46 and 0.20 and transmission loss values in the range of 25–33 dB and 25–42 dB, respectively. Results revealed that the leather cutting waste panels were characterized by interesting thermal and acoustic performance, which are of the same order of magnitude of other residual-based insulation panels. The other analyzed properties confirmed the potential application in building insulation.

Keywords Leather cutting waste · Thermal conductivity measurements · Acoustic characterization · Thermal stability · Building insulating systems

Introduction

Energy efficiency and environmental issues are becoming fundamental themes for the modern society, to guarantee a livable planet to future generations. In this context, the construction and building sector can be considered a major "polluter", since it consumes a relevant quantity of energy (about 40% of the world consumption), water (about 25%), resources (about 40%), and it is responsible for a large part of the carbon dioxide emissions [1]. Most of the energy is consumed during the building use phase (e.g. heating, ventilation and air conditioning systems) and a large part is lost through heat dispersion [2, 3]. Research on thermal insulation materials still represents an open issue to be investigated, to improve both the energy savings opportunities of future buildings.

Next to energy consumption, also noise can be considered a critical typology of pollution, strictly correlated to negative effects on the human health (e.g. stress, hearth disease) [4]. Noise reduction techniques and materials should be investigated to maximize the comfort in building structures [5].

For this reason, a large number of conventional/innovative synthetic (e.g. plastic, vacuum insulation panels, aerogel [6]) and natural (e.g. mineral wool [7], sheep wool [8], wood [9], and cellulose [10]) materials have been developed and launched in the market.

Scientific literature includes hundreds of studies about the development and experimental verification of insulation materials, based on renewable resources or wastes. In addition to thermal and noise insulation properties, this kind of materials are connected to lower environmental impacts, embodied energy, resource consumption and pollution emissions [11, 12].

✉ M. Barbanera
m.barbanera@unitus.it

1 Department of Economics, Engineering, Society and Business Organization, University of Tuscia, 01100 Viterbo, Italy

2 Department of Engineering, University of Perugia, Via G. Duranti 67, 06125 Perugia, Italy

3 Department of Ecological and Biological Sciences (DEB), Tuscia University, Viale dell'Università, snc, 01100 Viterbo, Italy

Published online: 06 April 2020

Among them, the most common are certainly the bio-based materials [13]: agricultural wastes, as rice husk, food crop by-products, cereal straw, etc.[14–17], particles of sunflower, and corn stalks [3, 18], palm tree surface fibers and leaflets [19, 20], bamboo powder [21], fibers derived from marine plants [22], residues from reed and cork [23], spent coffee grounds [24].

Industrial and domestic waste flows, in combination with other synthetic and/or natural substances, are also largely used in the sector of building insulation panels. Binici et al. [25] investigated the sound insulation, thermal conductivity and radioactivity properties of a light-weight construction material prepared using chipboards, fly ash, cotton waste and epoxy resin. Arenas et al. [26] focused on the development of road noise barriers based on bottom ash-based porous concrete with sound absorbing properties. Acoustical properties have been also investigated by Ghofrani et al. [27], who tried to improve the performance of a plywood panel, using waste tire rubbers. Many literature studies are focused on reusing plastic waste to prepare materials with interesting acoustic and thermal insulation properties [28, 29].

The last relevant category of materials used in building applications is certainly the textile wastes, used as alternative thermal insulation solutions [30, 31].

This paper aims to contribute to the abovementioned state of the art by investigating the feasibility of the use of finished leather scraps for the preparation of innovative panels for thermal-noise building insulation. Currently, leather and leather goods industry play an important role in the world economy. Leather material is used in many different sectors (e.g. furniture, automotive, footwear) and the demand for such products increased in the last decades [32]. During leather goods manufacturing, multiple wastes are generated, especially during the cutting step, when leather pieces are cut from the entire hides. Depending on the application and on the shape/dimension of the cut panels, it can be estimated that the 25–60% in weight of the initial hide constitutes scraps [33]. Considering an average weight of 225 kg for an entire hide, in the worst case 152 kg represents the cutting wastes [34]. These data demonstrate the scale of the problem and the need to investigate possible reuse solutions for this waste flow. Most of the existing literature studies about the leather industry wastes focus on the reuse/recycling of wastes generated by tanneries, which carry out chemical/mechanical treatments to transform fresh/salt/dried animal skins into a stable material, the leather [35–38]. Only few works investigate the reuse of finished leather wastes for production of composite materials [39, 40], regenerated leather [41], or insoles [42].

In this context, the aim of the present paper is the development of an insulation panel from finished leather scraps, deriving from the manufacturing of leather bags. Other than proposing a new insulation material, the main motivation of the present study is the definition of a sustainable end of life option for leather scraps. The leather was shredded, mixed with glue, and pressed to prepare samples for the testing phase. Thermal characteristics, acoustic properties, fire, and hygrothermal performance of recycled leather cutting waste-based boards are presented and compared with other insulation materials available on the market.

Materials and methods

Samples preparation and description

Finished bovine leather cuttings were provided by an Italian company in the province of Viterbo, which produces leather bags (Fig. 1a). Cutting step is one of the first operations during the manufacturing of leather goods and actually this kind of waste, generated from the leather sheets, is disposed to landfill causing a serious environmental hazard. Leather cuttings were firstly chipped, using a hammer chipping machine model TRITO 25/66 (ISVE, Italy), with a 3-cm

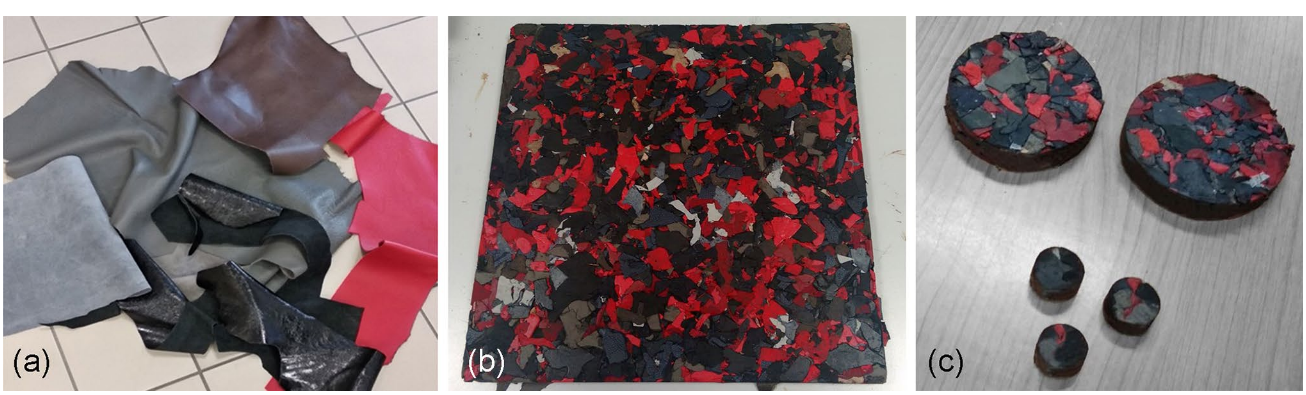

Fig. 1 Finished bovine leather cuttings used in this study: loose material (**a**), square panel built for the thermal measurements (LCW-b) (**b**), and large and small samples investigated in the Kundt's tube apparatus (thickness: 28 mm on the left, 18 mm on the right side) (**c**)

sieve. Polyvinylacetate (PVA) glue was added at room temperature to the leather chips as an adhesive in a proportion of 5% by weight, along with distilled water at a ratio of 12% by weight. In particular, commercial PVA containing polyvinyl alcohol as emulsifying agent was used in liquid form, characterized by the following properties: density: 1100 kg/m^3, solid content: 60%, viscosity: 36,500 mPa s. Moreover, PVA was chosen as adhesive agent thanks to its low degree of toxicity and also since in the building sector the operative temperatures are lower than its melting point (220–230 °C), beyond which the mechanical performance of PVA adhesive weakens [43].

The paste was mixed by hand at room temperature and was then poured into a stainless steel mold (0.36 m × 0.36 m) (Fig. 2). A non-adhesive paper was applied on the mold's walls, so that the mixture did not bond to the surfaces. Then the paste was covered by another stainless steel plate and cold compacted at 30 ton, using a hydraulic press (TOYO: Model TL30). After the pressing operation, the four screws at the corners of the mold were tightened and the material was left under pressure for 48 h. The leather board was then removed from the mold and it was kept in oven at 70 °C for 24 h, to remove exceeding water. Leather boards produced according to this procedure were used to make specimens of different shapes and sizes for the acoustic and thermal tests. In particular, for all the tests, the samples were pre-conditioned at a relative humidity of 57%RH and a temperature of 25 °C, to bring the panel under the typical environmental condition.

A square sample (28-mm thick, named LCW-b) was obtained by means of a cutter, to have the dimensions of 0.3 m × 0.3 m request by the thermal apparatus (Fig. 1b).

Cylinder later cutting waste samples were obtained from two panels with different thicknesses (18 and 28 mm average values), by means of a cylindrical hole cutter (Fig. 1c); due to the nature of the material, the thicknesses of the panels were not constant. At least two samples of each diameter (100 mm and 29 mm) and each thickness were available for testing without defects, cracks, and inhomogeneity.

The main features of the examined samples are reported in Table 1; in general, their thicknesses ware higher than the ones of the panels from which they were derived, due to the cut. For this reason also the densities are not the same for all the acoustic samples. However, the densities calculated after weighting the samples with an electronic precision balance were very similar (in the 600–680 kg/m^3 range). Only one of the 100-mm samples was characterized by a lower density, equal to 570 kg/m^3.

Table 1 Main features of the examined samples for acoustic measurements

Panel	Sample	Diameter (mm)	Density (kg/m^3)
LCW-a 18-mm average thick	L1	100	650
	L2	100	570
	S1	29	660
	S2	29	640
	S3	29	600
LCW-b 28-mm average thick	L3	100	610
	L4	100	670
	S4	29	600
	S5	29	680

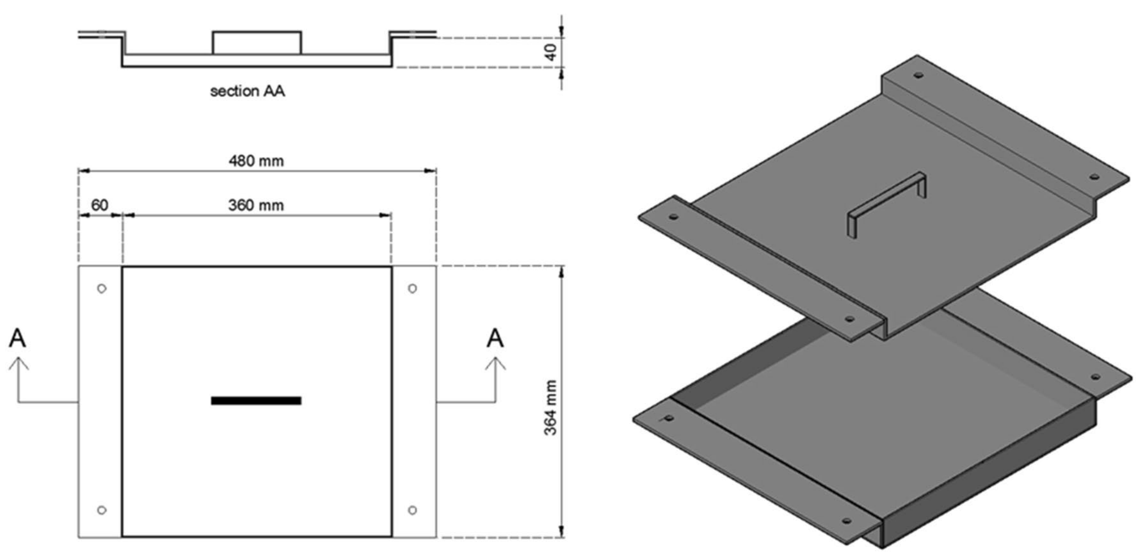

Fig. 2 Sketch on the mold used for production of the leather board

Thermal characterization by means of small-hot box system

The apparatus for thermal tests is the small hot box [44], an original system developed at the Laboratory of Environmental Control of the Department of Engineering in Perugia. The method is based on the steady-state heat transfer and the tests are carried out thanks to the thermal flux meter methodology in steady-state conditions. The system is composed of a hot chamber, well insulated from the environment thanks to a sandwich wall of wood and polystyrene, with a λ value equal to 0.023 W/mK (U value of the total package equal to 0.12 W/m^2 K). The mobile side of the box allows the positioning of the sample, thanks to an opening (0.3 m × 0.3 m dimensions, for a total area of 0.09 m^2). The box is heated by means of an internal heating wire (inside temperatures about 45–50 °C), whereas the Laboratory room represents the cold side of the system (external temperatures about 20–25 °C). The mean temperature difference between hot and cold side of the sample during the test is kept higher than 20 °C. A heat flow meter is positioned on the center of the sample and 8 thermoresistances are used for the surface temperature measurements. The thermal conductivity (λ in W/mK) is calculated as reported in (1) considering the mean surface temperatures of the hot and cold sides (T_{sH} and T_{sC}, respectively) during the tests, the heat flux through the sample (q) and the total thickness of the specimen (s):

$$\lambda = \frac{q}{T_{sH} - T_{sC}} \quad \text{(W/mK)}. \tag{1}$$

Considering equal to ± 5% and ± 0.10 °C the precisions of the thermal flux meter and of the thermoresistances, respectively, the accuracy can be estimated and it is in the 4–6% range for all the tests.

The relative uncertainties (type B) are calculated in compliance with JCGM 100:2008 [45]: the values are related to the fluctuation of the measured quantities during the test. It is possible to calculate the mean value ($\bar{x}_i$) for each measured quantity (T_{sH}, T_{sC}, q) following the hypothesized distribution and the uncertainty $u(x_i)$. The absolute uncertainty of the thermal conductivity $u(\lambda)$, obtained by considering the partial derivatives of λ with respect to the quantities taken into consideration, is given by Eq. (2). The relative value of the uncertainty is represented in Eq. (3):

$$u(\lambda) = \sqrt{\sum_{i=1}^{n} \left[\left(\frac{\partial \lambda}{\partial x_i} \right)^2 \cdot u^2\left(\bar{x}_i\right) \right]} \tag{2}$$

$$\dot{u}(\lambda) = \frac{u(\lambda)}{\lambda}. \tag{3}$$

Acoustic measurements

Sound absorption coefficient (α) and sound insulation (transmission Loss, TL) properties of the leather cutting waste were investigated considering the influence of the pane thicknesses. Environmental parameters in the laboratory (atmospheric pressure, air temperature, and relative humidity) were recorded at the beginning of each test, immediately after microphone calibration, to avoid channel phase displacement errors. The normal incidence absorption coefficient was measured using two-microphone impedance tube (Brüel & Kjær, model 4206), in compliance with ISO 10534-2 Standard [46]. The sound pressure was measured at the same time in two microphone positions (1/4-in. condenser pressure-field microphones, with an open circuit sensitivity of about 4 lV/Pa) after placing the sample inside the tube, and the transfer function was calculated. The acoustic energy ratio of the incidence wave absorbed by the sample (absorption coefficient, α) was related to the sound reflected back to the source side.

Moreover, the noise reduction coefficient (NRC) of the sample was calculated by mathematically averaging, rounded to the nearest multiple of 0.05, the absorption coefficient in the one octave band at the frequencies 250, 500, 1000, and 2000 Hz. It was developed for measurements carried out in reverberating rooms; in the present paper, NRC was used only to easily compare the acoustic performance of the tested samples.

A four microphone transfer function method was used to characterize the sound insulation performance of the material; transmission loss measurements were carried out in the Kundt's tube [47, 48]. TL is proportional to the logarithm of the sound transmission coefficient in function of frequency; it is defined as a ratio of sound energy transmitted through a material to the amount of sound energy incident on its source side. TL is determined by a two-load method: two successive acquisitions were determined for each sample, by modifying the tube extremity features installing alternately a reflective and an absorbing material, and the sound pressure was acquired in four fixed-microphone positions.

In both the absorption and insulation tests, two instrument configurations were used, to investigate the entire 200–5000 Hz frequency range: the large tube (cylindrical samples of 100-mm diameter) allows to measure in the 200–1600 Hz frequency range, while the small tube (cylindrical samples of 29-mm diameter) in the 400–5000 Hz range. The samples installed inside the tubes are shown in Fig. 3.

Thermogravimetric analysis

Thermal stability of finished bovine leather cuttings was evaluated by carrying out thermogravimetric (TGA)

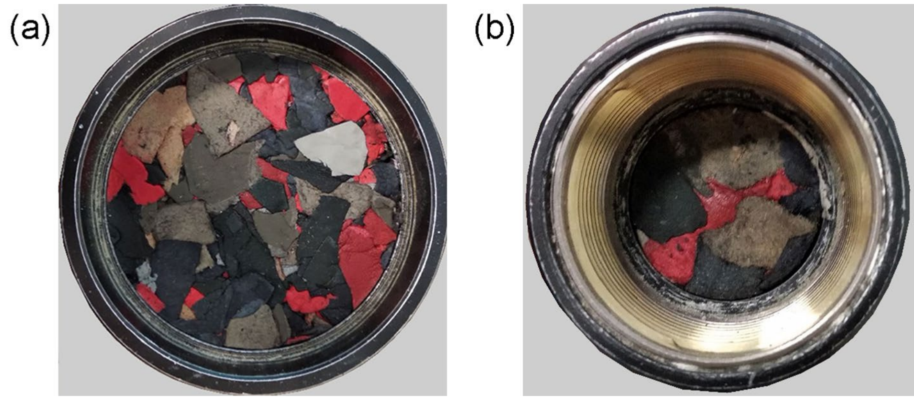

Fig. 3 Samples installed in the Kundt's tube apparatus: large tube (**a**), and small tube (**b**)

analysis in a LECO TGA-701, according to standard test method ASTM E1131-08. About 0.2 g of leather powder was heated up from ambient temperature (approximately 25 °C) to 900 °C under air atmosphere with a flow rate of 3.5 L/min and a heating rate of 10 °C/min. From the TG and the respective differential (DTG) curves, the temperatures at 5% and 50% of weight loss (T5% and T50%), and the maximum thermal degradation temperature were calculated.

Water contact angle (WCA) measurements

Static contact angle measurements were used to investigate the wettability of the leather scraps. The water contact angles were assessed using the sessile drop method in air by a FTA1000 Analyzer (Dinwiddie Street, Portsmouth, VA). Deionized water drops of 20 µL (high performance liquid chromatography grade water) were placed on the material surface at room temperature, and measurements were recorded 5 s after the liquid made contact with the surface. Ten independent determinations at different sites were averaged.

Hygrothermal performance

Water vapor resistance factor µ of the cylindrical leather cutting samples (100-mm diameter and 18-mm thick) was carried out by a dry cup test containing silicagel as desiccant, according to UNI EN ISO 12572 Standard [49]. It shows how greater the resistance of the material is with respect to an equally thick layer of stationary air at the same temperature.

Before testing, Mazzali C330G5 climatic chamber (600 × 700 × 680 mm internal dimensions,—40–150 °C temperature range, and 15–100% relative humidity range) available at the University of Perugia was used to precondition the samples. They were stored (at 23 ± 5 °C and 50 ± 5% RH) until three successive daily determinations of their weight were within 5%.

For the test, the specimens were arranged and sealed in transparent cups (Fig. 4), allowing better control of salt solutions. At the bottom of each cup, it was put a minimum depth of 15 mm of silicagel (granules of 1–3 mm dimensions) with color indicator, leaving an air space of 15 ± 5 mm between the desiccant and the sample. The assemblies were then placed in the temperature and relative humidity controlled test chamber with environmental conditions in compliance

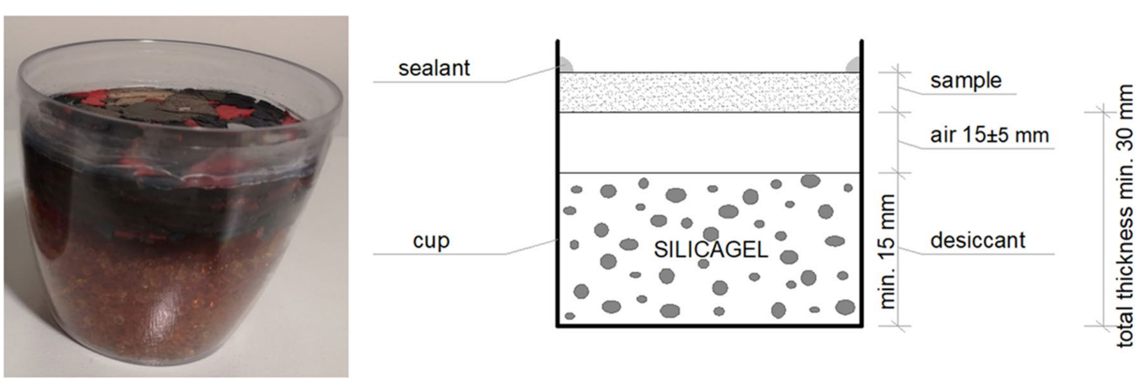

Fig. 4 Hygrothermal measurements (dry cup method): samples preparation

with [49]. Because of the different partial vapor pressure between the test cup and the chamber, a vapor flow occurs through the permeable samples. Periodic weighings (one every 24 h) of the samples with a precision balance were carried out to evaluate the rate of water vapor transmission in the steady-state conditions.

The mass change rate ($\Delta m_{12} = \frac{m_2 - m_1}{t_2 - t_1}$ in kg/s) of each sample was calculated by measuring the masses (m_1 and m_2 in kg) of the test assembly at successive times of weighings t_1 and t_2 (in s), respectively, as shown in Eq. (4):

$$\Delta m_{12} = \frac{m_2 - m_1}{t_2 - t_1}, \tag{4}$$

G was calculated as the mean of five successive determinations of Δm_{12}. The final value of G was obtained when each of the last five successive determinations of Δm_{12} was within ± 5% of G.

The water vapor resistance factor μ was calculated as:

$$\mu = \frac{\delta_{air}}{\delta}, \tag{5}$$

where the water vapor permeability of air δ_{air} was assumed equal to $2.05 \cdot 10^{-10}$ kg/(msPa), with a measured barometric pressure at 23 °C inside the apparatus of 985 hPa; the water vapor permeability δ was calculated as:

$$\delta = W \cdot d \tag{6}$$

$$W = \frac{G}{A \cdot \Delta P} \tag{7}$$

$$A = \frac{A_{up} + A_{low}}{2}, \tag{8}$$

where W is the water vapor permeance; d the thickness of the sample; A the arithmetic mean of the free upper and lower surface areas; and ΔP is the 1404 Pa, water vapor pressure difference across sample.

Ignitability test

The ignitability test, according to the standard UNI EN ISO 11925-2 [50], is used to evaluate the reaction of building materials to fire. In this test method vertically oriented specimens are exposed to a small burner flame, simulating the flame of a match or a lighter (Fig. 5).

Three specimens with 90 mm × 250 mm × 20 mm dimensions were used to perform the reaction to fire test. The specimens were conditioned before the test to a constant mass at a temperature of 23 °C ± 2 °C and a relative humidity of 60% ± 5% RH.

Testing was carried out in a combustion chamber, where a burner flame 20 mm height was applied on the center line of the specimen, 40 mm above the bottom edge (surface exposure), for 15 s. In particular, the flame was brought into contact with the specimen at an angle of 45°. For each test specimen was recorded whether an ignition occurred (flaming longer than 3 s), whether the flame tip reached 150 mm above the flame application point and the time at which this occurs. Furthermore, the occurrence of burning particles was observed with filter paper placed below the specimen (whether ignition of the filter paper occurred). In particular, if the flame tip does not reach a 150-mm limit, then the material is classified as class E, according to standard ISO 13,501–1 [51]. At this regard other three tests with a period of 30 s are also carried out to evaluate if the material could reach higher classes.

Fig. 5 Specimen placed in the frame for ignitability test

Results and discussion

Thermal properties

To evaluate the thermal conductivity of the leather cutting waste panel, two tests were carried out in the small-hot box apparatus, only considering the higher thickness of the samples (28 mm, panel LCW-b). The first test was carried out considering a temperature inside the box equal to 45 °C, the second one has set-up temperature of 50 °C. Both the measurements lasted for 2 h and in both cases the difference between the air temperature into the box and the air temperature into the room (hot and cold sides, respectively) was more than 20 °C.

In Table 2 the main results of the test are presented: the thermal conductivity of the panel is 0.108 W/(mK) and 0.104 W/(mK), respectively, for the 45 °C and 50 °C set-up hot temperatures. These values are related to mean surface temperatures of 33–35 °C, therefore, for mean surface temperatures of 23 °C and 10 °C (values that are considered for the referred λ reported in the technical sheets of the manufacturers) the thermal conductivities should be slightly lower (about 0.100 W/(mK) at 10 °C, a value approximately estimated by means of the Standard ISO 10456 [52]) by considering a mean value of the f_t conversion coefficient of similar materials.

The uncertainty u values obtained for both the tests are about 4.6%, thanks to the small variations of the parameters during the tests (maximum thermal heat flux variations of 4–5 W/m^2).

For the sake of completeness, the trends of the temperatures and of the heat flux are shown in Fig. 6 for the first test (45 °C in the hot chamber). To compare the results with reference thermal conductivities of standard heat insulating materials, some values are reported: at 10 °C the thermal conductivities of mineral wood, expanded polystyrene and extruded polystyrene are in the 0.03–0.04 W/(mK) range. Slightly higher is the value of cellulose panels (about 0.05 W/(mK)) [53]. The leather cutting waste panels perform worse (0.100 W/(mK)). Nevertheless,

Table 2 Thermal result of the investigated sample: thermal flux meter methodology (small hot box)

Sample	Hot side test condition (°C)	s_{TOT} (m)	ΔT_a (°C)	q (W/m^{2}K)	$T_{s,average}$ (°C)	λ_{TOT} (W/mK)	$\dot{u}$ (λ) (%)
LCW-b	45	0.028	20.86	47.92	32.68	0.108	4.68
LCW-b	50	0.028	25.68	57.23	35.26	0.104	4.61

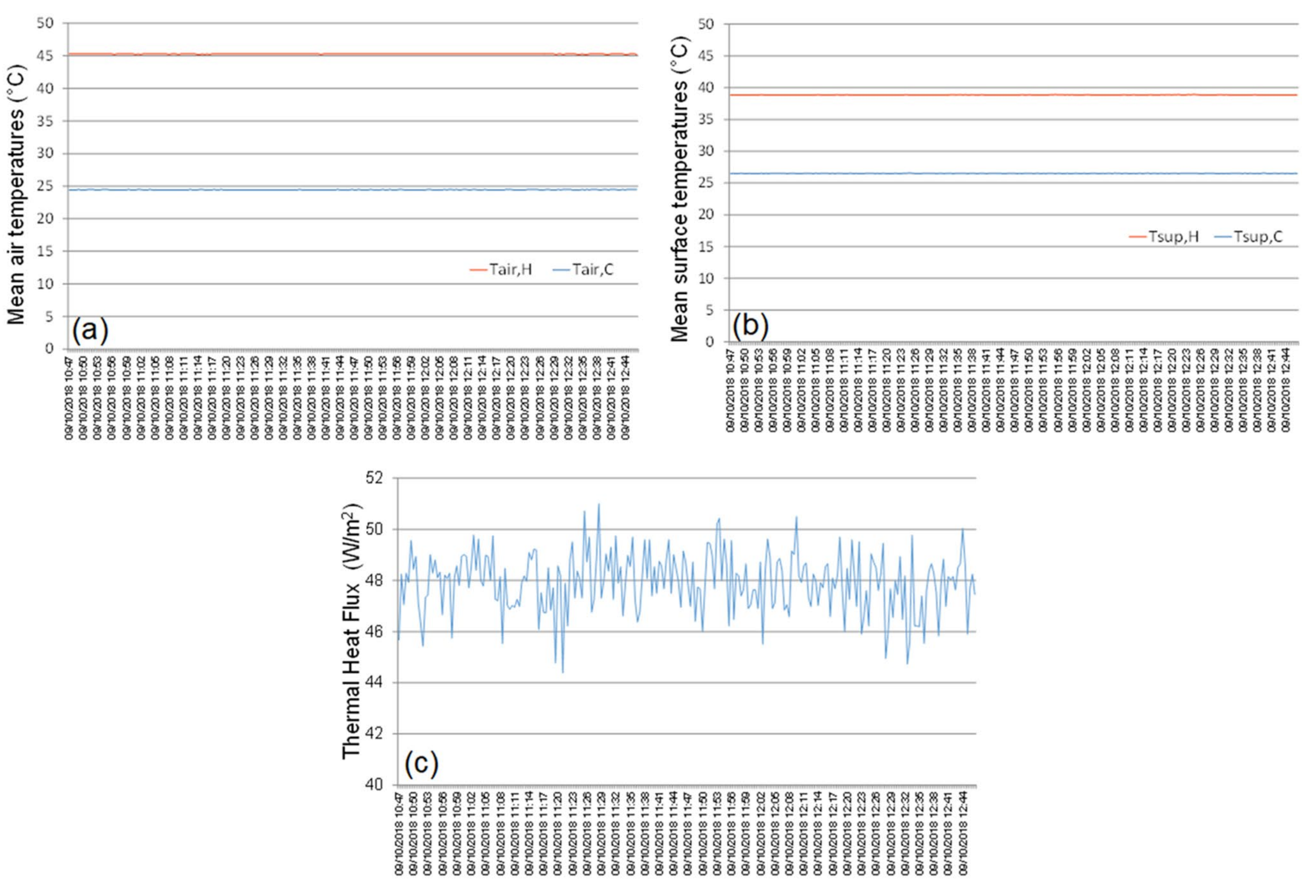

Fig. 6 The trends of the monitored parameters during the test: **a** air temperatures (°C), **b** surface temperatures (°C), **c** heat flux (W/m^2)

the value is comparable to the ones of other frequently used materials such as rubber based panels and cork (0.07–0.14 W/(mK)).

Acoustic absorption and transmission loss properties

Several measurements were carried out for each sample, also modifying its position inside the apparatus and an average trend was obtained in the 200–5000 Hz frequency range, considering the samples with the most similar density. The normal incidence absorption coefficient vs. frequency is plotted in Fig. 7a, depending on the thickness.

A peak of absorption characterizes both the samples at low frequencies: by increasing thickness, the peak moves towards lower frequencies, as expected. Moreover, α value increases with the thickness: absorption coefficient peak values of about 0.31 are found for LCW-a (about 18-mm average thickness) at 1200 Hz and ca. 0.60 for LCW-b (about 28-mm average thickness) at 600 Hz, and the corresponding NRC values is more two times higher (0.46 rather than 0.20).

The transmission loss levels for the two samples are shown in Fig. 7b; only the TL levels measured in the 400–1600 Hz range are discussed, being these frequencies the more representative in the building insulation field. The samples have a similar trend for TL. Globally, the sound insulation performance of the LCW-b is higher than the one of LCW-a, due to the higher thickness of the leather cutting waste, according to the literature [47]. The transmission loss levels are significant: they are in the 25–33 dB and 25–42 dB range for the 18-mm and 28-mm thick samples, respectively. At 500 Hz the sound insulation is the same for two different thicknesses (about 28 dB), while it raises of about 4 dB at 1000 Hz with a 28-mm thick pane.

Thermal stability of finished bovine leather cuttings

Figure 8 shows the TG and DTG curves of finished bovine leather cuttings. It could be noted that thermal decomposition occurs in three stages. The first step, from room temperature to about 210 °C, can be attributed to the removal of residual moisture. The second mass loss stage ends around 405 °C and it is mainly due to the thermo-oxidative decomposition of collagen with a well-defined DTG peak. The weight loss in the second stage is 42.8%.

The last thermal decomposition step was mainly due to internal residue oxidation [3] and the combustion of sample was completed at around 820 °C, achieving a total weight loss of 91.7%. The temperature at which the sample starts to lose its mass (T5%) was equal to 249 °C, while the T50% temperature at which the sample loses 50% of the initial mass was achieved at 373 °C. Furthermore, the maximum degradation temperature occurred at 336 °C, where about 40% of initial mass was lost. This thermal behavior of the finished bovine leather cuttings shows that it has a potential to be employed as an insulation material up to 249 °C, where the initial degradation starts. This result was mainly due to the chromium-tanning stabilization process of the bovine leather; in fact, the alkali Cr salts lead to formation of hydrogen bonds, with the hydroxyl groups present in the leather, and the leather fibrous texture is preserved through crosslinking in bulk during the thermal heating [54].

Wettability properties

Water vapor transmission is a multi-stage process. The analysis of the water wettability of the surface permits to better analyze the first stage of this process, since the

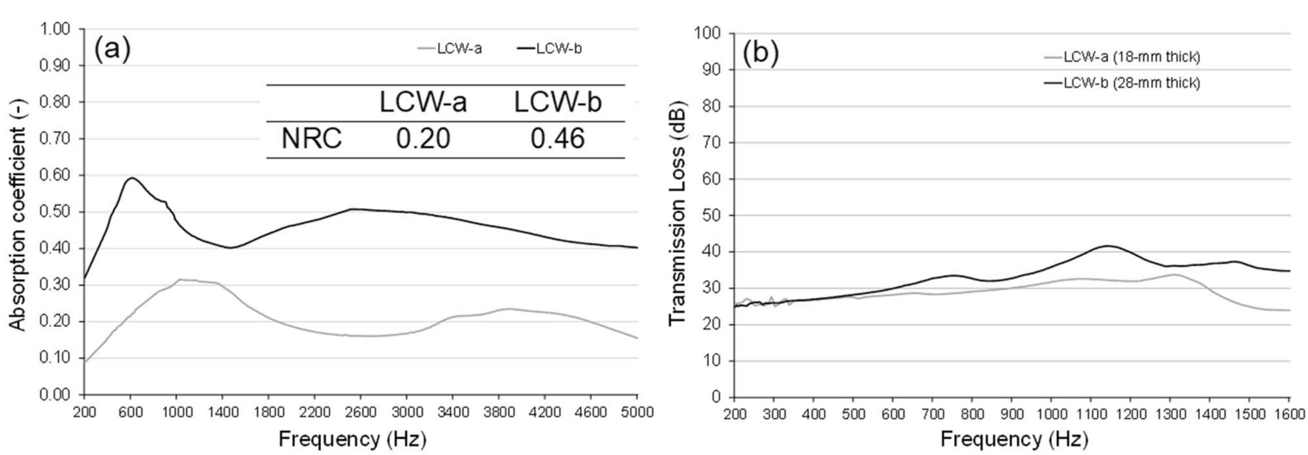

Fig. 7 Normal incidence absorption coefficient (**a**) and normal incidence transmission loss (**b**) of leather cutting waste: influence of thickness

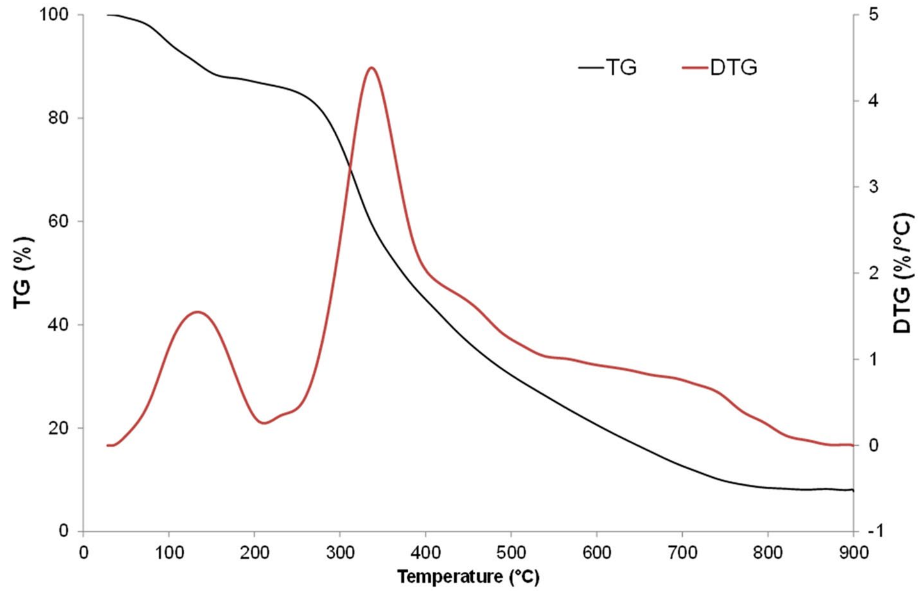

Fig. 8 TG/DTG profiles of bovine leather cuttings under air temperature

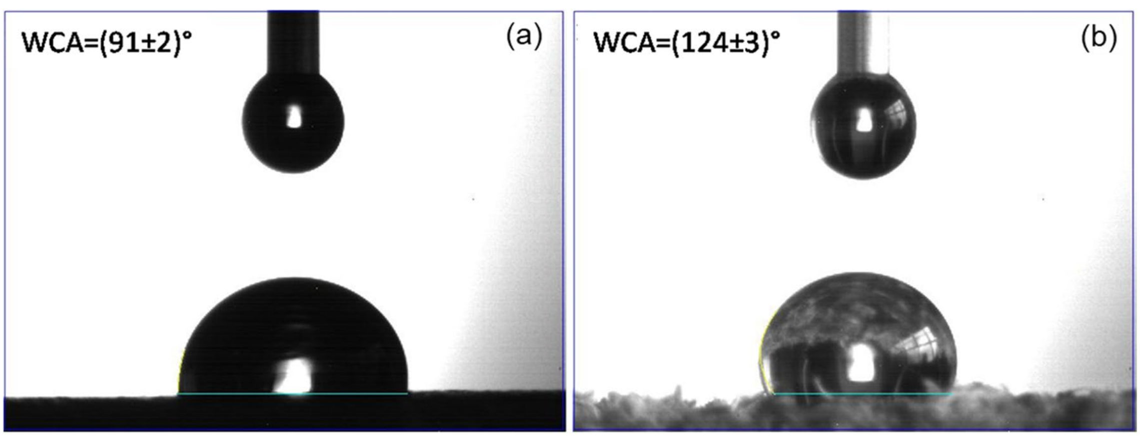

Fig. 9 WCA images and values of upper (**a**) and lower (**b**) leather surface

material surface is the first part of the panel that came in contact with the water. The finished leather scraps have two different kind of surfaces in terms of morphology and chemical treatments, and the insulation panel is composed by randomly oriented scraps of both surfaces, as shown in Fig. 1, hence the wettability properties of both leather surfaces were investigated.

Figure 9 shows the WCA images and values of upper (A) and lower (B) leather surface, respectively [55]. The reported WCA values of 91° and 124° for the upper and lower leather surfaces underline a hydrophobicity behavior of the finished leather scraps, that permits well to analyze and understand the results of the permeability properties of the insulating panels [56]. The high WCA of the surface reduces the transfer vapor on the internal part of the panels by reducing the water permeability.

Table 3 Water vapour resistance factor results

Sample	δ_{air} (kg/(msPa))	G (kg/s)	A (m^2)	ΔP (Pa)	μ
LCW	$2.05 \cdot 10^{-10}$	$4.14–4.63 \cdot 10^{-9}$	$7.85 \cdot 10^{-3}$	1404	27–30

Permeability properties

The stability of the permeability tests was achieved in different times for each leather cutting sample (4–7 weeks from the beginning of the experimental campaign). Values of water vapor resistance factor in the 27–30 range were obtained, as shown in Table 3. The permeability performances are better than those of many traditional vegetable

Fig. 10 Single-flame source (surface exposure) test results within 15 s (left) and 30 s (right) fire exposure. Burned areas are highlighted by white dotted lines

Table 4 Results of ignitability test

Test duration	15 s	30 s
Flame impingement	Surface exposure	
Board ignition	Yes	Yes
Reaching a flame height of 150 mm above the attachment point	No	No
Ignition of filter paper	No	No
Maximum flame level during the test (cm)	25 ± 0.3	8.8 ± 0.4

fibers, such as wood ($\mu = 3$–10), cork ($\mu = 5$–10), hemp, flax, corn, and coir ($\mu = 1$–3), and mineral fibers ($\mu = 5$–8 for expanded vermiculite and perlite and $\mu = 1$–5 for glass or stone wool). μ values obtained are close to the expanded polystyrene ($\mu = 20$–80) and polyurethane ($\mu = 30$–100) [57].

Ignitability test results

The standard single-flame source test was employed to evaluate the ignition ability of the LCW insulating material. Figure 10 shows the specimens after applying the flame. Table 4 reports the main results of the tests; it can be noticed that LCW were ignited but the flame did not reach over 150 mm within the 15 s duration of the test, indicating that class E could easily be obtained. Moreover, by increasing the test duration up to 30 s, reaching higher classes is possible, but additional testing according to standard ISO 13501-1 is needed. At the point where the flame was applied, the samples ignited during the flame exposure while they extinguished immediately after the flame was removed, showing that LCW can resist a small flame attack without significant flame spread for short periods.

Comparison analysis with other residual-based insulation panels

The public attention is focused to the recovery of waste materials obtained both from the industrial processes and from the agricultural cultivations, due to the great importance of the sustainability. Therefore, many discarded materials are reused for the development of building applications. Numerous studies were conducted up today, with particular attention to natural resources. In this paragraph a comparison between the results obtained for the studied panel and other building insulating systems properties was carried out. The thermal insulation and the acoustic absorption performance were analyzed; also the permeability properties were analyzed for same residual-based insulation materials. As concerning the acoustic point of view, NRC index (noise reduction coefficient) was calculated, as defined in the previous paragraphs. It should be noted that the comparison of this parameter is significant only considering similar thickness because of the different trends of the absorption coefficients. The main results obtained in different research studies are shown in Table 5.

The comparison includes several typologies of mineral, synthetic, and natural fiber materials. It is possible to observe that the behavior of the leather cutting waste panel is similar to the granulated rubber, also considering the same thickness (1.7–1.8 cm). In fact, the thermal conductivity of these panels is higher than 0.1 W/mK and the NRC value is approximately the same (0.20). Both the leather and the rubber have the same texture and density and they are generally more efficient for the acoustic insulation considering their high surface mass.

As concerning the natural fibers, the thermal conductivities are always lower (0.036–0.076 W/mK), but the acoustic absorption properties are aligned with the leather panel ones (NRC = 0.22–0.31). As expected, the NRC coefficient increases with the thickness, as you can see for the LCW and the sheep wool samples.

A wood panel (composed by glued wood fibers) has good thermal behavior in comparison with LCW-b (thickness comparable of about 3 cm). Nevertheless, it is possible to observe a worst acoustic absorption performance (NRC is 0.25, lower than 0.46, the one of LCW-b). The waste paper samples have thermal conductivities variable in 0.036–0.050 W/mK: the sample with polyethylene can be compared to the LCW-a from the acoustic point of view (equal thickness) and it is possible to observe that the NRC is about two times higher.

Table 5 Thermal and acoustic properties of different insulating panels composed by industrial or agricultural waste

Material	Thickness (mm)	Thermal conductivity (W/mK)	NRC	μ (–)	References
LCW-a	*18*	*0.108*[a]	*0.20*	*30*	–
LCW-a	*28*	*0.108*[a]	*0.46*	*27*	–
Kenaf	60	0.038[b]	0.60	4	[58, 59]
Glued wood fiber	30	0.065[b]	0.25	3–5	[44, 58, 60]
Cork scraps	17	0.055[a]	0.22	5–10	[17, 60]
Rice husk	16	0.070[a]	0.23	41[c]	[17]
Coffee chaff	10	0.076[a]	0.33	390[c]	[17]
Granulated rubber	17	0.135[a]	0.20	–	[17]
Glued waste paper	10	0.036[a]	0.30	–	[17]
Glued waste paper + polyethylene fiber	18	0.038[a]	0.38	–	[17]
Glued waste paper + wool paper	50	0.050[a]	0.47	2–4	[17]
Sheep wool-a	20	0.036[a]	0.31	3	[60–62]
Sheep wool-b	40	0.038[a]	0.57	3	[60–62]

*Calculated at a mean surface temperature of about 30–32 °C

[b]Calculated at a mean surface temperature of about 10 °C

[c]Measured by the same methodology of LCW samples

Italic values indicate that the highlighted material tested

Finally, considering the water vapor resistance factor, it is possible to observe that the μ value obtained for the leather cutting waste panels is higher than the values measured for other mineral fiber-based panels, such as the sheep wool, the kenaf, the wood and the cork (values of about 3–10). It means that the studied material allows excellent moisture transfer.

Future works should investigate the use of natural binders, to decrease the environmental impact of the production process of the panel and, at the same time, to obtain a higher porosity for increasing the sound absorption properties at high frequency.

Conclusion

Leather goods industry generates multiple waste, connected both to the treatments to transform fresh/salt/dried animal skins into leather and to the cutting phase, when pieces are cut from the entire hides. Scientific literature is mainly focused on the animal skin treatments, less on the use of finished leather wastes.

In the present paper the recycling of scraps deriving from the manufacturing of leather bags is investigated; they are used as secondary raw material for the fabrication of a thermal and noise insulation panel for building applications.

The panel was fabricated using leather pieces cut by a chipping machine, glued, and pressed by means of a hydraulic press. Thermal and acoustic characterization was carried out to evaluate the suitability of the proposed solution as insulation material in building applications. In addition to thermal insulation and soundproofing, hygrothermal and fire-resistant performance were also evaluated.

The thermal conductivity of the panel, measured by means of the small-hot box apparatus, is about 0.10–0.11 W/(mK) at 33–35 °C, with a measurement uncertainty of about 4.6%. When compared to various typologies of mineral, synthetic and natural fiber materials, the behavior of the leather cutting waste panel is similar to the one of granulated rubber panels, characterized by a thermal conductivity of about 0.13 W/mK. Natural fibers show lower values of the thermal conductivity, in the 0.036–0.076 W/mK range, such as glued wood fiber panels.

On the other hand, the acoustic performance of the leather panel, measured by means of a Kundt's tube, is rather good, showing NRC values of 0.20 and 0.46 for 18-mm and 28-mm thickness, respectively, with α-peak values of 0.31 and 0.60. When compared to other panels made of recycled materials, NRC values are higher than the ones found for glued wood fiber panels (0.46 vs. 0.25, same thickness of about 30 mm) and of the same order of the ones found for glued waste paper + wool fiber panel (0.46 vs. 0.47), but 50-mm thick. Transmission loss values are also very interesting, varying in the 25–33 dB and 25–42 dB for the 18-mm and 28-mm thick samples, respectively.

Furthermore, thermal stability analysis showed that the proposed panel can be employed as insulation material up to about 250 °C, widely above building applications; in particular, it meets the requirements for inclusion in the class E reaction to fire. Also the wettability and permeability properties of the material confirmed its potential application in building insulation since the hydrophobicity behavior and the low water permeability protect the finished leather scraps from against biological attacks (fungi, parasites, etc.).

In conclusion, the proposed panel, made of scraps deriving from the manufacturing of leather bags, is a good alternative to traditional materials used in building sector for thermal and noise insulation and for sound absorption, showing similar performance of other panels made using industry and agriculture waste. The added value of the proposed solution and, in general, of recycled materials is their lower environmental impact with respect to conventional solutions and the advantage to use waste which often need to be disposed with high costs.

Acknowledgements Authors wish to thank DiMar Group s.r.l. (Viterbo, Italy) for supplying the materials, and Dr. Giulia Luci and Dr. Stefano Rosciani for their precious contribution during the experimental campaigns.

References

1. United Nation Environment Programme, Environment for development. https://www.unep.org/sbci/AboutSBCI/Background.asp. Accessed 20 Nov 2019
2. Aksogan O, Resatoglu R, Binici H (2018) An environment friendly new insulation material involving waste newsprint papers reinforced by cane stalks. J Build Eng 15:33–40
3. Binici H, Eken M, Dolaz O, Aksogan O, Kara M (2014) An environmentally friendly thermal insulation material from sunflower stalk, textile waste and stubble fibres. Constr Build Mater 51:24–33
4. Reixach R, Del Rey R, Alba J, Arbat G, Espinach FX, Mutjé P (2015) Acoustic properties of agroforestry waste orange pruning fibers reinforced polypropylene composites as an alternative to laminated gypsum boards. Constr Build Mater 77:124–129
5. Del Rey R, Alba J, Arenas JP, Sanchis VJ (2012) An empirical modelling of porous sound absorbing materials made of recycled foam. Appl Acoust 73:604–609
6. Baetens R, Jelle BP, Gustavsen A (2011) Aerogel insulation for building applications: a state-of-the-art review. Energy Build 43:761–769
7. Orlik-Kozdon B (2017) Assessment of the application efficiency of recycling materials in thermal insulations. Constr Build Mater 156:476–485
8. Corscadden KW, Biggs JN, Stiles DK (2014) Sheep's wool insulation: a sustainable alternative use for a renewable resource. Resour Conserv Recycl 86:9–15
9. Cetiner I, Shea AD (2018) Wood waste as an alternative thermal insulation for buildings. Energy Build 168:374–384
10. Lopez Hurtado P, Rouilly A, Vandenbossche V, Raynaud C (2016) A review on the properties of cellulose fibre insulation. Build Environ 96:170–177
11. Leiva C, Arenas C, Vilches LF, Alonso-Farinas B, Rodriguez-Galan M (2015) Development of fly ash boards with thermal, acoustic and fire insulation properties. Waste Manag 46:298–303
12. Pedroso M, de Brito J, Silvestre JD (2017) Characterization of eco-efficient acoustic insulation materials (traditional and innovative). Constr Build Mater 140:221–228
13. Liu LF, Li HQ, Lazzaretto A, Manente G, Tong CY, Liu QB, Li NP (2017) The development history and prospects of biomass-based insulation materials for buildings. Renew Sustain Energy Rev 69:912–932
14. Palumbo M, Formosa J, Lacasta AM (2015) Thermal degradation and fire behavior of thermal insulation materials based on food crop by-products. Constr Build Mater 79:34–39
15. Antonio J, Tadeu A, Marques B, Almeida JAS, Pinto V (2018) Application of rice husk in the development of new composite boards. Constr Build Mater 176:432–439
16. Bakatovich A, Davydenko N, Gaspar F (2018) Thermal insulating plates produced on the basis of vegetable agricultural waste. Energy Build 180:72–82
17. Buratti C, Belloni E, Lascaro E, Merli F, Ricciardi P (2018) Rice husk panels for building applications: thermal, acoustic and environmental characterization and comparison with other innovative recycled waste materials. Constr Build Mater 171:338–349
18. Faustino J, Pereira L, Soares S, Cruz D, Paiva A, Varum H, Ferreira J, Pinto J (2012) Impact sound insulation technique using corn cob particleboard. Constr Build Mater 37:153–159
19. Ali ME, Alabdulkarem A (2017) On thermal characteristics and microstructure of a new insulation material extracted from date palm trees surface fibers. Constr Build Mater 138:276–284
20. Masri T, Ounis H, Sedira L, Kaci A, Benchabane A (2018) Characterization of new composite material based on date palm leaflets and expanded polystyrene wastes. Constr Build Mater 164:410–418
21. Nguyen DM, Grillet AC, Bui QB, Diep TMH, Woloszyn M (2018) Building bio-insulation materials based on bamboo powder and bio-binders. Constr Build Mater 186:686–698
22. Hamdaoui O, Ibos L, Mazioud A, Safi M, Limam O (2018) Thermophysical characterization of Posidonia Oceanica marine fibers intended to be used as an insulation material in Mediterranean buildings. Constr Build Mater 180:68–76
23. Barreca F, Martinez Gabarron A, Flores Yepes JA, Pastor Perez JJ (2019) Innovative use of giant reed and cork residues for panels of buildings in Mediterranean area. Resour Conserv Recycl 140:259–266
24. Lachheb A, Allouhi A, El Marhoune M, Saadani R, Kousksou T, Jamil A, Rahmoune M, Oussouaddi O (2019) Thermal insulation improvement in construction materials by adding spent coffee grounds: an experimental and simulation study. J Clean Prod 209:1411–1419
25. Binici H, Gemci R, KucuKonder A, Solak HH (2012) Investigating sound insulation, thermal conductivity and radioactivity of chipboards produced with cotton waste, fly ash and barite. Constr Build Mater 30:826–832
26. Arenas C, Leiva C, Vilches LF, Cifuentes H, Rodriguez-Galan M (2015) Technical specifications for highway noise barriers made of coal bottom ash-based sound absorbing concrete. Constr Build Mater 95:585–591
27. Ghofrani M, Ashori A, Rezvani MH, Ghamsari FA (2016) Acoustical properties of plywood/waste tire rubber composite panels. Measurement 94:382–387
28. Benkreira H, Khan A, Horoshenkov KV (2011) Sustainable acoustic and thermal insulation materials from elastomeric waste residues. Chem Eng Sci 66:4157–4171
29. Agoua E, Allognon-Houessou E, Adjovi E, Togbedji B (2013) Thermal conductivity of composites made of wastes of wood and expanded polystyrene. Constr Build Mater 41:557–562
30. Briga-Sa A, Nascimento D, Texeira N, Pinto J, Caldeira F, Varum H, Paiva A (2013) Textile waste as an alternative thermal insulation building material solution. Constr Build Mater 38:155–160
31. Tilioua A, Libessart L, Lassue S (2018) Characterization of the thermal properties of fibrous insulation materials made from recycled textile fibers for building applications: theoretical and experimental analyses. Appl Therm Eng 142:56–67
32. UNIDO (2010) Future trends in the world leather and leather products industry and trade. United Nations Industrial Development Organisation, Vienna

33. UNIDO (2000) Wastes generated in the leather products industry, 14th meeting of the UNIDO leather panel (Meeting summary). United Nations Industrial Development Organisation, Vienna
34. UNIDO (2000) Mass balance in leather processing. United Nations Industrial Development Organisation, Vienna
35. Krummenauer K, de Oliveira Andrade JJ (2009) Incorporation of chromium-tanned leather residue to asphalt micro-surface layer. Constr Build Mater 23:574–581
36. Lakrafli H, Tahiri S, Albizane A, Bouhria M, El Otmani ME (2013) Experimental study of thermal conductivity of leather and carpentry wastes. Constr Build Mater 48:566–574
37. Lakrafli H, Tahiri S, Albizane A, El Houssaini S, Bouhria M (2017) Effect of thermal insulation using leather and carpentry wastes on thermal comfort and energy consumption in a residential building. Energy Effic 10:1189–1199
38. Şaşmaz S, Karaağaç B, Uyanık N (2018) Utilization of chrome-tanned leather wastes in natural rubber and styrene-butadiene rubber blends. J Mater Cycles Waste Manag 21:166–175
39. Senthil R, Inbasekaran S, Gobi N, Das BN, Sastry TP (2015) Utilisation of finished leather wastes for the production of blended fabrics. Clean Technol Environ Policy 17:1535–1546
40. Teklay A, Gebeyehu G, Getachew T, Yaynshet T, Sastry TP (2017) Conversion of finished leather waste incorporated with plant fibers into value added consumer products—an effort to minimize solid waste in Ethiopia. Waste Manag 68:45–55
41. Senthil R, Hemalatha T, Kumar BS, Uma TS, Das BN, Sastry TP (2015) Recycling of finished leather wastes: a novel approach. Clean Technol Environ Policy 17:187–197
42. Senthil R, Sastry TP, Saraswathy G, Das BN, Gobi N (2018) Leather insole with acupressure effect: new perspectives. J Polym Environ 26:175–182
43. Chaabouni O, Boufi S (2017) Cellulose nanofibrils/polyvinyl acetate nanocomposite adhesives with improved mechanical properties. Carbohydr Polym 156:64–70
44. Buratti C, Belloni E, Lunghi L, Barbanera M (2016) Thermal conductivity measurements by means of a new 'small hot-box' apparatus: manufacturing, calibration and preliminary experimental tests on different materials. Int J Thermophys 37:47
45. JCGM 100 (2008) GUM 1995 with minor corrections evaluation of measurement data—guide to the expression of uncertainty in measurement
46. ISO 10534-2 (1998) Acoustics—determination of sound absorption coefficient and impedance in impedance tubes—part 2: transfer-function method
47. Jung SS, Kim YT, Lee YB, Cho S, Lee JK (2008) Measurement of sound transmission loss by using impedance tubes. J Korean Phys Soc 53:596–600
48. Barnard AR, Rao DM (2004) Measurement of sound transmission loss using a modified four-microphone impedance tube, NOISE-CON, Baltimore, Maryland, 12–14 July
49. UNI EN ISO 12572 (2016) Hygrothermal performance of building materials and products—determination of water vapour transmission properties: Cup method
50. UNI EN ISO 11925-2 (2010) Reaction to fire tests. Ignitability of products subjected to direct impingement of flame. Part 2: single-flame source test
51. UNI EN 13501-1 (2018) Fire classification of construction products and building elements. Part 1: classification using data from reaction to fire tests
52. ISO 10456 (2007) Building materials and products—hygrothermal properties—tabulated design values and procedures for determining declared and design thermal values. ISO, Geneva
53. Buratti C (2019) Translucent silica aerogels: properties, preparation and applications. Nova Science Publishers, New York
54. Rosu L, Varganici CD, Crudu AM, Rosu D (2018) Influence of different tanning agents on bovine leather thermal degradation. J Therm Anal Calorim 134:583–594
55. You X, Gou L, Tong X (2016) Improvement in surface hydrophilicity and resistance to deformation of natural leather through O_2/H_2O low-temperature plasma treatment. Appl Surf Sci 360:398–402
56. Ibrahim M, Nocentini K, Stipetic M, Dantz S, Caiazzo FG, Sayegh H, Bianco L (2019) Multi-field and multi-scale characterization of novel super insulating panels/systems based on silica aerogels: thermal, hydric, mechanical, acoustic, and fire performance. Build Environ 151:30–42
57. https://www.iuav.it/SISTEMA-DE/Archivio-d/approfondi/materiali-/Materiali_Isolanti.pdf. Accessed 17 Dec 2019
58. Berardi U, Iannace G (2015) Acoustic characterization of natural fibers for sound absorption applications. Build Environ 30:1–13
59. https://www.masacoustics.it/wp-content/uploads/2013/11/datasheet-kenaf-60-kg-30mm.pdf. Accessed 9 Jan 2020
60. https://www.anit.it/wp-content/uploads/2015/02/Parte-7_v3.pdf. Accessed 9 Jan 2020
61. Zach J, Korjenic A, Petránek V, Hroudová J, Bednar T (2012) Performance evaluation and research of alternative thermal insulations based on sheep wool. Energy Build 49:246–253
62. Zacha J, Korjenicb A, Petráneka V, Hroudováa J, Bednarb T (2012) Performance evaluation and research of alternative thermal insulations based on sheep wool. Energy Build 49:246–253