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Rice husk panels for building applications: Thermal, acoustic and environmental characterization and comparison with other innovative recycled waste materials

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HIGHLIGHTS

- Rice husk panels for building applications were experimentally analysed.
- Thermal, acoustic and environmental performance were investigated.
- A comparison with other waste recycled materials was performed.
- A new experimental apparatus for thermal measurements was used.
- Primary embodied energy and greenhouse gas emissions were determined.

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ABSTRACT

In building applications, recycled waste materials are becoming promising acoustic absorbers and thermal insulating solutions in order to reduce the environmental impact. The aim of the research is to evaluate the thermal, acoustic, and environmental performance of recycled waste panels consisting of rice husk (RH) produced by gluing and pressing the raw material. Its acoustic and thermal performance were compared with the ones of six panels composed by other recycled materials (cork scraps, end-life tires, coffee chaff, waste paper, textile fiber mats, wool fiber scraps), assembled with similar techniques. Thermal resistance of RH is equal to 0.59 m^2K/W, in the same order of magnitude of many traditional systems. Sound absorption coefficients were measured by means of the impedance tube. All the panels present acoustic absorption comparable with traditional ones (peak values 0.87–0.99). RH peak value is 0.87, while the maximum values are obtained for cork and wool fiber scraps (1 and 0.97 respectively). Life cycle analysis, performed in compliance with ISO 14040 showed the best environmental performance for the production of 1 m^2 of RH and coffee chaff panels. Taking in account their acoustic and thermal behaviour, the wool fiber scraps presents a very good performance.

1. Introduction

The minimisation of carbon emissions resulting from the use of buildings increases relative importance of a building's life-cycle stages [1–3]. Thus, measures to control and reduce the environmental impacts of the entire construction chain have become a priority, in particular the production phase of building materials. The increased investment in near-zero buildings is also promoting the use of passive solutions for the envelope, resulting in increased insulation thicknesses of the walls all over the world [4]. As a consequence, the contribution of these materials to the life cycle environmental impact is also gaining momentum [5–7]. In addition, the growing environmental awareness throughout the world triggered a shift towards developing environment friendly materials from recycled ones [8,9]. Some non-conventional materials are emerging, especially the ones of natural origin, which still present rare applications in the building field. Volf et al. tested several materials such as raw sheep wool, wood fibre, hemp, flax, compressed straw bale in order to evaluate their thermal, moisture, and biological properties [10].

The novelty of this paper consists in presenting the results on thermal and acoustic characterization and life cycle analysis of an innovative recycled waste materials obtained from the discards

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of the rice processing (Rice Husk, named in the paper with the abbreviation RH). This material can be used for the fabrication of panels for building applications: its acoustic and thermal behaviour can be compared with other panels made of cork scraps (COR), end-life granulated tires (ELT), coffee chaff (CC), waste paper pressed and glued with polyethylene fibers mat (WP1), waste paper pressed and glued (WP2), and waste paper pressed and glued with wool fibers (WP3). Among these applications, cork and end-life granulated tires have been employed for years and they are included in the market as traditional building panes. Coffee chaff panels and the systems composed by waste paper glued and pressed are new materials and their properties are currently being analyzed.

Rice is the third most produced commodity in the world after sugar cane and maize, with more than 740 million tons per year [11]. Rice straw and rice husks were preliminary investigated by Izhar et al. and Sakamoto et al. [12,13] showing their useful characteristics of sound absorption. Yarbrough et al. [14] focused on thermal insulation performance of particleboards made of rice hulls, and found thermal conductivity values in the 0.046–0.057 W/mK range, comparable with the ones of coconut or sugarcane fibers. Yang et al. [15] analyzed the sound absorption coefficient of three composite materials made of rice straw and wood (10, 20, and 30% of rice in weight). The panel with 10% showed a sound absorption coefficient higher than particleboards, fiberboard, and plywood panels. None of the above mentioned studies on rice by products investigated the glued rice husks, which could be an innovative recycled material for the building sector. Recently, the rice husk ash was also inserted in Portland cement mortars in place of sea sand, in order to obtain improvement in terms of compressive strength [16]. Finally, another interesting study analyzed the potential of poppy (Papaver somniferum Linnaeus) husk for manufacturing wood-based particleboards [17]: poppy husk particles reduce the formaldehyde emissions and contribute to improve the physical and mechanical requirements of the panels.

Cork scraps deriving from the waste of the wine cops production are another valuable natural material for building applications [18]. Cork is very interesting from a sustainability perspective because it allows many environmental services such as forest preservation, biodiversity conservation, and wildfire prevention. Currently, in Sardinia (Italy) cork oak bark are only exploited about 20,000 km^2 of existing 36,000 km^2 [19]. Fernandes et al. [20] tested the fire resistance and the acoustic insulation of cork/HDPE (high density polyethylene) and cork/PP (polypropylene) composites, and found out that the presence of cork improves both properties. Experimental tests [21] were also carried out on samples composed by cork granules: they showed good sound absorption characteristics, low thermal conductivity, and low density, with best absorption results for the smallest granules. Vasconcelos et al. [22] investigated blocks made of cork and chalk for internal partition walls. Tests carried out by Tiuc et al. [23] on samples composed by a layer of cork of thickness of 3 mm, a layer of particles coming from the shredding of tires (diameter: 1–3 mm), and a polyurethane binder (15%) showed differences between the values of the absorption coefficient by changing the measurement side.

Leading car manufacturers are now producing vehicles which incorporate up to 20% of recycled waste [24,25], but end-life tires constitute a great proportion of total automotive waste. Different studies [26–28] showed that the absorption coefficient usually decreases by increasing the size of rubber granules. In particular, Maderuelo-Sanz et al. [26] found that the most appropriate size granules are in the 1–3 mm range. In the study conducted by Horoshenkov et al. [27], the relationship between percentage of binder and porosity is almost linear. Maderuelo-Sanz et al. [28] investigated the influence of the binder on the sound absorption and found the best results for samples made with 0.71–1 mm particle size granules, concentration of the 15% binder and 20% of degree of consolidation.

Coffee is one of the most widely consumed beverages [29], with a production of 8 million metric tons per year [30]. During the roasting process, the residual coffee chaff is completely removed and the ground roasted coffee beans are finally used for coffee beverage production. Coffee chaff is an industrial waste readily available in large amounts, waiting for a definition of its potential value-added uses [31].

Concerning the waste paper systems, insulation panels with cellulose as the main raw material were developed and analyzed in [32] and it was observed that they are suitable as acoustic correction systems, especially a panel type composed by waste paper and wool fibers. Natural fibers systems [33] showed acoustic properties strongly depending on the methods of production; their behaviour cannot be theoretically evaluated due to the lack of homogeneity. Yeon et al. developed a building material made from waste newspapers and magazines with good thermal insulation and sound absorption properties [34].

In the present paper rice husk (RH) panels were fabricated and studied from different perspectives and the results were related with the same performance of other traditional and innovative boards made with the same construction technique: the raw materials were glued and the panels were slightly compressed. The thermal resistance and the acoustic absorption coefficient were evaluated by means of two experimental campaigns. The thermal flux meter method [35] was used for the thermal analysis and the impedance tube method for the acoustic investigations, in compliance with ISO 10534-1, 2 [36,37]. Life Cycle analysis was also performed, in compliance with ISO 14040 series requirements [38,39]. A deep comparison analysis was carried out taking into account also the results obtained for other innovative waste materials in other experimental campaigns: all the aspects were investigated (thermal, acoustic, and environmental analysis).

2. Materials and method

2.1. Samples description

A company based in Lombardy (Italy) supplied rice husk, since it deals with rice derivatives production and distribution. Rice husk is deriving from the paddy rice husking process, the rough rice (unpolished) after threshing. The percentage of rice husk over paddy rice is variable depending on the variety, and it can be in the 17–23% range by weight. The used shells have a length of about 9 mm and a width of 1 mm. Rice husk contains 75–90% organic matter such as cellulose, lignin and mineral components, such as silica, alkalis, and trace elements [40]. Their content depends on rice variety, soil chemistry, climatic conditions, and even the geographic localization of the cultures [41].

All the tested samples were made in laboratory, in the form of disks of 2.9 and 10 cm diameter, for acoustic measurements, and as square panels of 300 × 300 mm for thermal ones (Fig. 1). For the realization of the samples, it was used a cold-water-based polyurethane glue, with a density of 1.000 kg/m^3 and a percentage present of 2.5% of the total weight. The percentage was determined after preliminary tests, in order to find the percentage necessary for an optimal consistence of the sample. The used polyurethane-based glue was a polyurethane adhesive in aqueous dispersion and it was found to be the ideal binder for bonding the type of used row material. In particular, this adhesive was found to be easily applied by spray technique and made it possible to achieve the desired results with low doses. Furthermore, two support panels of plasterboard (each thick 6 mm), one for each side of the recycled waste material, were employed for the thermal measurements'

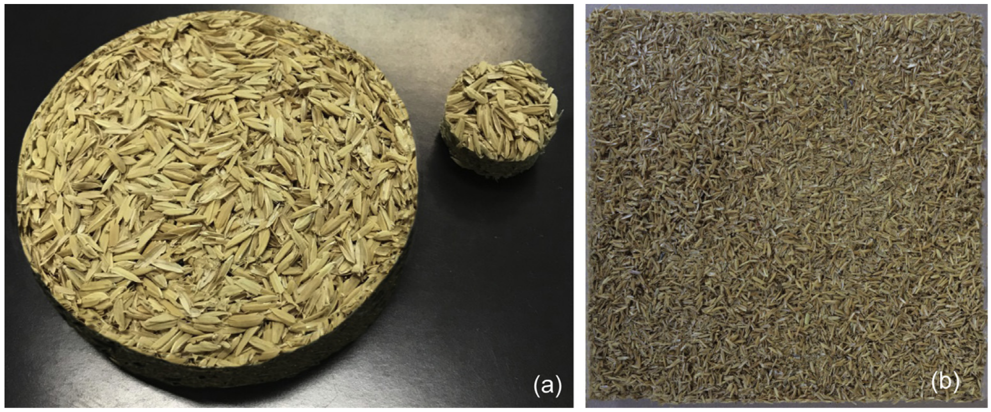


Fig. 1. Rice husk (RH) glued: a) acoustic and b) thermal measurement samples.

sample; its total thickness was equal to 53.13 mm, considering the contribution of plasterboard panels. The main features of the examined samples are reported in Table 1; the considered samples are the best obtained in terms of compactness and geometric shape. The density is related to the finished waste sample, considering the presence of the glue used for the production.

2.2. Thermal characterization by means of Small hot box system

The thermal properties of rice husk were evaluated with an experimental apparatus, named *Small Hot Box* (Fig. 2) [35], designed and built at the Laboratory of Environmental Control, Department of Engineering (University of Perugia). The Small Hot Box facility is composed of a hot chamber (external dimensions 0.94 × 0.94 × 0.50 m): its outer walls are made of very thick insulation (about 200 mm) covered with wood panels (20 mm thickness), in order to minimize the heat flux through the walls. A heating wire (maximum power 50 W) placed inside the hot room allows constant temperatures inside the room. A sandwich structure, composed of two wood panels with a middle layer of expanded polyurethane, constitutes the closure side of the system: an opening (0.3 × 0.3 m dimensions, for a total area of 0.09 m^2) for the sample placement is present in the central part. The cold side of the system is the Laboratory room, not confined with outside, and kept at constant temperature thanks to the HVAC system. The temperature difference between hot and cold side was maintained at least equal to 20 °C. The tests are in general carried out by the thermal flux meter methodology: the heat flux (q) is measured through a thermal flux meter installed in the central part of the sample; 8 termoresistances installed on the sample (four sensors each side) allow measuring the surface temperatures. The value of thermal resistance is obtained as shown in (1):

$$R = \frac{T_{sH} - T_{sC}}{q} \quad \left[\frac{m^2K}{W}\right] \tag{1}$$

where T_{sH} and T_{sC} are the mean surface sample temperatures in the Hot and Cold sides during the tests.

The error calculated considering the precision of the probes (±5% for the thermal flux meter, ±0.05 °C for the thermal resistances) is about 4–6% for all the tests.

The thermal resistance of rice husk (R_i) was evaluated considering the Eq. (2): the total thermal resistance (R), in fact, is composed by the plasterboard panels' contribution (R_p) and the insulating one (R_i). It is possible to evaluate thermal conductivity of the only insulating recycled layer λ_i by using this equation.

$$R = R_p + R_i = \frac{2s_p}{\lambda_p} + \frac{s_{RH}}{\lambda_{RH}} \quad \left[\frac{m^2K}{W}\right] \tag{2}$$

2.3. Characterization by air-flow resistance, porosity and tortuosity

Other three parameters as air-flow resistivity, porosity, and tortuosity were also determined in order to contribute to the description of the acoustic behaviour of rice husk samples: they allowed to calculate the intrinsic acoustic properties, the complex wave number, and the characteristic impedance of a sound-absorbing homogeneous material.

The flow resistance and porosity characteristics were measured by means of an experimental set–up purposely built at in the Department of Civil Engineering and Architecture, University of Pavia. The flow resistance method described in the standard ISO 9053 [42] was applied: the goal of the method is to maintain a stationary unidirectional air flow through the test sample, in order to measure the pressure difference between the two free faces of the specimen. The apparatus consists of a cylinder closed at the bottom by the sample equipped with two pressure taps; a water tank for the production of the air flow; a rubber hose, necessary to connect the water tank and the cylinder; a differential manometer (Dwyer 477AV, accuracy ±0.5%, pressure range 0–966 Pa, maximum measurable pressure 5 psi).

The porosity is determined by comparing air volumes of a measurement and a reference chamber, using the method developed in [43]. The experimental equipment is represented in Fig. 3.

The sample is placed in the measurement chamber (b) and the two chambers are set at atmospheric pressure.

During the test, the reduction of volume in the measurement chamber due to the introduction of the sample is compensated by increasing the volume of a piston (c) connected to it.

After each movement of the water-drawing piston (d), the chambers return to atmospheric pressure by opening the valve

Table 1
Rice husk: samples characteristics.

	Test (dimensions)	Thickness [mm]	Density [kg/m^3]	Glue [%]
Rice husk (RH)	Acoustic (29 mm and 100 mm diameter)	16.40	170	2.5
	Thermal (300 × 300 mm)	41.13		

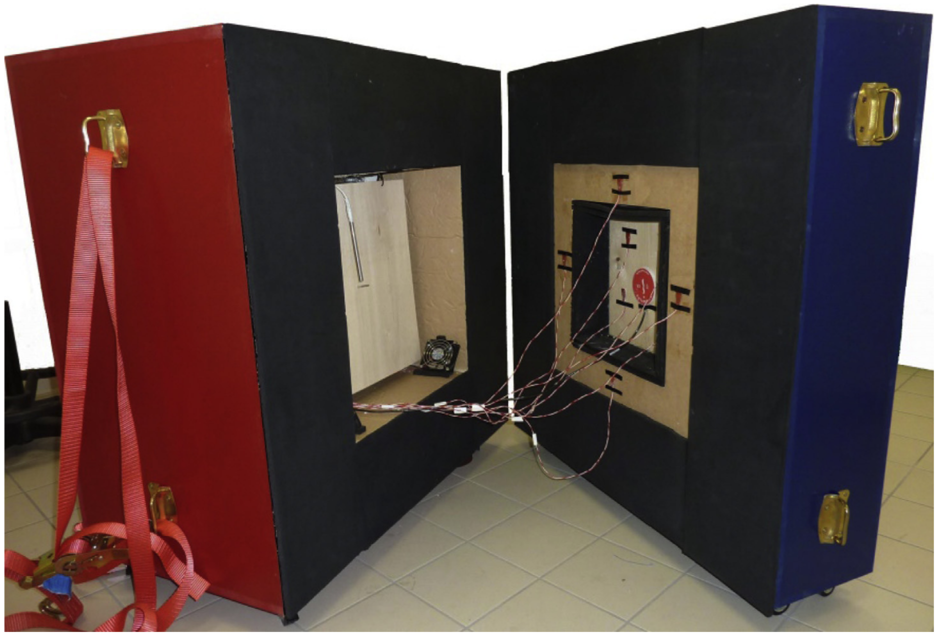


Fig. 2. Rice husk sample inserted in the Small Hot Box apparatus.

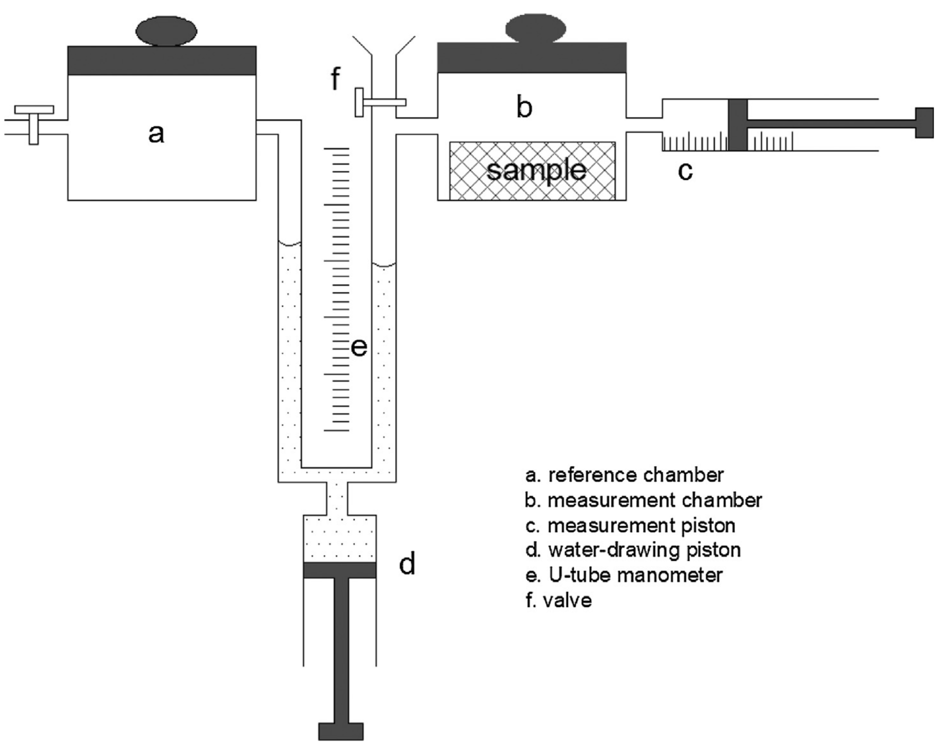


Fig. 3. Porosity measurement equipment.

(f). The difference in levels between the two branches of the manometer is equal to zero when the volume in the measurement piston corresponds to the volume of solid of the porous sample. The proportion of solid and then the porosity is obtained by dividing the volume of solid by the volume of the sample:

$$\Omega = \frac{V_{solid}}{V_{sample}} \tag{3}$$

The tortuosity was calculated through the porosity values. The calculation was performed using the Berryman formula [44], which is used in the Literature for granular materials:

$$q = 1 + \frac{1-\Omega}{2\Omega} \tag{4}$$

where Ω is the porosity.

2.4. Sound absorption coefficient measurements

The two-microphone impedance tube – Brüel & Kjær, model 4206, was used for the measurement of the absorption coefficient of the samples [45,46]. Two configurations were considered: the first one (large samples, diameter equal to 100 mm) allows the measurement in the 100–1600 Hz frequency range, the second one (small samples, diameter equal to 29 mm) in the 500–6400 Hz range. A sound source is mounted at one end of the impedance tube, and the sample is placed at the other end; the loudspeaker generates broadband, stationary random sound waves, which propagate as plane waves in the tube, hit the sample, and reflect.

The propagation, contact, and reflection result in a standing-wave interference pattern due to the superposition of forward and backward travelling waves inside the tube.

For the sound absorption coefficient measurements, the sound pressure is acquired simultaneously in two fixed microphone positions and the corresponding complex transfer function using a two channel digital frequency analyzer is calculated. The acquired function allows to determine the sound reflection coefficient, and thus the value of the absorption coefficient [36,37].

The sample of rice husk inserted in the device is shown in Fig. 4, as an example of the large configuration.

Fig. 4. General view of the sample in the Kundt's Tube (large tube).

2.5. LCA analysis: methodology and input data

In order to assess and to compare the environmental performance of the rice husk panel, a Life Cycle Analysis was performed, in compliance with ISO 14040 series requirements [38,39].

The aim of the evaluation is the definition of the cumulative energy demand (CED) and the global warming potential (GWP 100 years) as environmental impact indexes associated to the panel production. The CED represents the energy (MJ/kg) consumed for the product manufacture. The global warming potential (GWP) quantifies the carbon footprint, basing on a relative scale which compares the specific GHG (Green House Gas) emissions with an equivalent mass of CO_2, whose GWP is by definition equal to 1.

The LCA analysis was performed by using Simapro 8 (PRé Consultants).

The functional unit (f.u.) is defined in compliance with ISO standards 14040 series [38,39]. In order to evaluate the environmental behaviour of the rice husk panel chain, 1 m^2 of manufactured panel was considered. Two additional functional units were introduced, in order to assess the life cycle of the panel from thermal and acoustic point of view and to perform the comparison with other waste recycled panels:

- the mass (kg) of insulating panel that involves a thermal resistance R equal to 1 m^2 K/W, according to a proposal of the Council for European Producers of Materials for Construction [47]:

$$f.u. = R \times \lambda \times \rho \times A \quad [kg] \tag{5}$$

where R is the thermal resistance equal to 1 (m^2 K/W); λ is the thermal conductivity of the panel in (W/m K); ρ is the density of the panel in kg/m^3; A is the area equal to 1 m^2;

- 1 absorption unit, as the corresponding panel area (m^2) calculated with the absorption coefficient, to evaluate panel application as sound absorber.

As concern the system boundaries, energy, mass flows, and environmental impacts were assessed from the production of the rice husk, to the manufactured end-product at company gate, following the "cradle to gate" approach. The production of rice husk determines no impact to the whole life cycle of the panel, because it is a byproduct of a different production chain and no energy consumptions are necessary to its reuse.

Concerning installation, maintenance, and end-of-life, the impacts were neglected because no data are available due to the prototype stage of the investigated materials. The system boundaries are shown in Fig. 5.

Three stages of the life cycle were considered: panel components supplying, transportation in all stages, and panel production. The panel production company is assumed to be in Pavia, Northern Italy. The manufacturers of rice husk are located at an average distance of 160 km from the company, because the rice production is concentrated in Piemonte and Lombardia regions.

Finally the Life Cycle Inventory was carried out. Data sources include foreground information, in which primary data were collected from the manufacturer of the panel and their components, background data, in which secondary data were taken from international Literature, and databases and tertiary data, from estimate models.

Rice husk is a co-product of other production processes and immediately available in its form, so only transportation impacts were considered. Glue production data were collected directly at

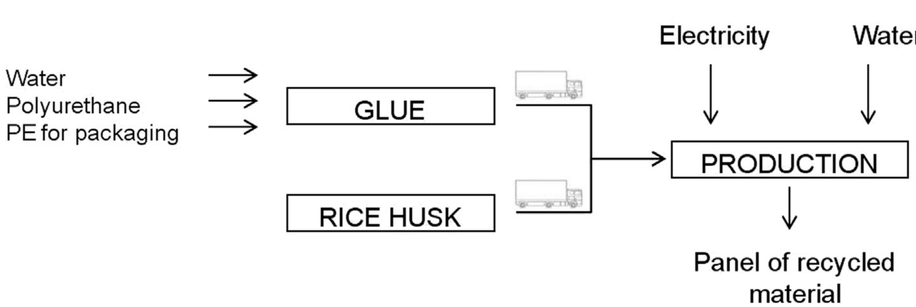


Fig. 5. System boundaries for the LCA analysis of the rice husk panel.

Table 2
Data inventory for components production and supplying stage (referring to 1 kg of produced material).

Material and energy inputs	Unit	Amount	Data source
Rice husk			
Transport (freight, lorry >2 metric ton, EURO5)	tkm	0.32	Ecoinvent
Glue			
Polyurethane	kg	0.5	Primary data
Water	kg	0.5	Primary data
Polyethylene for packaging	kg	0.0357	Assumption
Transport (freight, lorry >32 metric ton, EURO5)	tkm	0.6	Ecoinvent

Table 3
Data inventory for panel production stage (referring to 1 m^2 of produced panel).

Material and energy inputs	Unit	Amount	Data source
Electricity	kWh	0.04	Primary data
Water	kg	0.7	Primary data
Rice husk panel			
Rice husk weight	kg	2.39	Primary data
Glue weight	kg	0.40	Primary data

manufacturer, located at a distance of 300 km from the panel production site. The physical characteristics of the panels (density, weight, surface mass) were measured on the samples used for acoustic measurements. The transportations were modeled adopting generic data for a mean transport, provided by the Ecoinvent database. Distances were calculated as already described in the system boundaries. Background data for the eco-inventories of raw materials and energy sources (packaging materials, glue components, electricity) were obtained from the Ecoinvent database. In Tables 2 and 3 the inventory data for the panel components production and supplying phase and for the glued panel production are respectively reported.

2.6. Samples considered for comparison with rice husk panel

The performance of rice husk samples were compared and discussed in comparison with alternative traditional waste materials, such as cork scraps and granulated rubber, and new recycled ones (coffee chaff and panels of recycled paper and other scrap materials), purposely realized for the present study. In particular:

- the samples of cork (COR) are derived from the extraction on the cork oak bark, which undergoes a grinding process to obtain the granulate for making wine caps. The tested samples are coming from the waste of the wine caps industrial process from a company located in the northern of Sardinia region. In order to obtain the best results in terms of absorption and thermal properties, the granules chosen for this study have a size in 0.8–1 mm range;
- the granulated rubber samples (ELT) are provided by an Italian company that collects end-life tires coming from various regions of Northern Italy. The output of the process is crushed material of various sizes and types, depending on the intended final products: rubber chips (size 30–50 mm), granulated rubber (0.8–20 mm), powder rubber (<0.8 mm), and textile fibers. For the present study, granulated rubber with size in the 0.8–2.5 mm was used: this particular size presents characteristics that allow to achieve better sound absorption results compared to other particle sizes [27];
- the coffee chaff samples (CC), whose environmental and acoustic characteristics are widely discussed in [31], were investigated also in terms of thermal performance. The investigated samples are made of coffee chaff derived as the waste of the roasting process of an industry from northern Italy (Pavia).

Cylindrical (29 mm and 100 mm diameter) and square (30x30cm) specimens for each material were fabricated and studied with the same methodology described in the previous paragraph. Different glue percentages were used for each kind of row material; in order to accelerate the drying phase of the glue, the samples were placed in an oven for a time between 90 and 120 min at a temperature of 100 °C. This temperature was chosen because the curves of the thermogravimetric analysis test (TGA) showed that, for the granulated cork, the water loss occurs totally within a temperature of 100 °C and in a percentage equal to about 5% of the total initial weight. For the rubber, the water loss took place at temperatures below 180 °C, and was equal to 2% of the total weight of the tested material. For the ELTs granulate, the percentage of water lost was equal to 10%.Moreover, the properties of three panels constituted by recycled paper and other scrap materials [48], also investigated in a previous work [32] are considered in the discussion:

- WP1, composed by waste paper layer pressed of 10 mm thickness inserted between two panels of polyethylene fibers material (each 4 mm thick), joined by glue;
- WP2, a waste paper layer glued and pressed;
- WP3, a panel composed by 45 mm of glued wool fibers and 5 mm of waste paper pressed and glued (total thickness of 50 mm).

The main characteristics of the traditional and innovative recycled waste materials used for the comparison with the rice husk panel are reported in Table 4; the thickness of 300 × 300 mm samples is referred only to the contribution of recycled waste materials (support plasterboard panels are not considered). The rice husk has the smallest density (170 kg/m^3) and glue percentage (2.5%) when compared to other waste samples made manually in laboratory (cork, rubber, and coffee chaff). Furthermore, the thicknesses of recycled paper panels are the standard ones commercialized by the manufactures'; their density is very variable and the weight of glued wool fibers is lower than other samples (WP3 sample density equal to 110 kg/m^3).

3. Results and discussion

3.1. Thermal measurement

Thermal properties, measured by using the thermal flux meter methodology, are reported in Table 5. Several tests were conducted for each material considering different set point air temperature in hot chamber; the most significant results are shown with an air temperature of 45 °C. During measurements, lasted for about 2 h, all the surface temperatures were constant, with a maximum difference of about 0.5 °C on the cold side and 0.8 °C on the hot one. Furthermore, also the air-temperature trend in the hot chamber and in the laboratory (cold side), as the thermal flux, are constant, ensuring stationary test conditions; the air temperature

Table 4
Description of the samples used for the comparison with the rice husk panel.

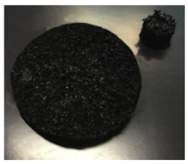
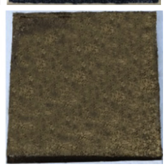
Sample	Picture	Sample dimensions [mm]	Thickness [mm]	Density [kg/m^3]	Glue [%]
Cork scraps COR	 	diameter 29 and 100 300 × 300	17.1 45.75	195	6
Granulated rubber ELT	 	diameter 29 and 100 300 × 300	16.8 41.14	550	5
Coffee chaff CC	 	diameter 29 and 100 300 × 300	9.40 29.66	350	5.5
WP1	 	diameter 29 and 100 300 × 300	18.00	605	13
WP2	 	diameter 29 and 100 300 × 300	10.00	646	21
WP3	 	diameter 29 and 100 300 × 300	50.00	110	13

Table 5
Thermal results of recycled waste sample: thermal flux meter methodology (Small Hot Box).

Sample	ΔT_{air} [°C]	T_{sH} [°C]	T_{sC} [°C]	ΔT_s [°C]	q [W/m^2]	R_i [m^{2}K/W]	λ_i [W/mK]	Relative uncertainty Type B [%]
RH	**20.62**	**42.20**	**29.28**	**12.92**	**20.04**	**0.58**	**0.070**	**±5.3**
COR	21.23	42.80	29.97	12.83	14.48	0.83	0.055	±4.7
ELT	20.86	41.28	30.30	10.98	30.39	0.30	0.135	±2.1
CC	20.44	41.85	31.14	10.71	24.01	0.39	0.076	±2.6
WP1	20.72	43.12	23.99	19.13	40.70	0.47	0.038	±7.2
WP2	21.33	43.23	24.52	18.71	66.82	0.28	0.036	±7.9
WP3	21.04	42.93	23.78	19.15	17.29	1.11	0.050	±11.0

difference is maintained in the 20.44–21.33 range, in compliance with [49]. Thermal conductivity of rice husk, cork, rubber, and coffee chaff samples is obtained with Eq. (2), considering a plasterboard panels' contribution equal to 0.057 W/mK (R = 0.21 m^{2}K/W), such as suggested in its technical sheet.

All the new recycled waste materials can be considered good thermal insulators (thermal conductivity varies in the 0.036–0.076 W/mK range); thermal conductivity of rice husk is about 0.070 W/mK, however it can be considered a significant insulator, comparable for example to the expanded vermiculite or of the same order of magnitude of innovative loose materials such as granular aerogels [45,50]. Thermal performance of COR and ELT (λ = 0.055 W/mK and λ = 0.135 W/mK, respectively) are better and data are in agreement with the Literature. The thermal insulation properties obtained for samples of recycled paper and other scrap materials (WP1, WP2, and WP3) are of the same order of the ones of many conventional insulators (such as glass or rock wool, λ = 0.040 W/mK). The relative uncertainties (type B) were calculated in accordance with JCGM 100:2008 [51]: the values are related to the fluctuation of the measured quantities during the test. For the specimens RH, COR, ELT, and CC the relative uncertainty is variable in the 2–5% range; for the waste paper materials the uncertainties were higher (7.2–11%) because of the flux values that are not very stationary during the selected tests: in fact these three panels are not very compact and regular in shape (Table 5).

3.2. Air-flow resistance, porosity and tortuosity

The difficulty in performing the flow resistance test was linked to the generation of an air flow that had to be enough slow in order to do not affect the measured values. As reported by the standard, the most reliable results are obtained by generating an air flow speed less than or equal to 0.5 mm/s; for higher speeds, the measure of flow resistance may be affected by the air speed and this would lead to underestimate the results. Therefore, it was decided to consider valid only the results corresponding to the smallest values of air speed. However it was remarked that flow resistance measurements show a good reproducibility.

The measured data of flow resistance, porosity, and tortuosity are reported in Table 6 for rice husk (RH) and for the other samples investigated for comparison. Rice husk (RH) shows the lowest value of flow resistance (11700 Pa s/m^3), about half with respect to ELT and COR, while coffee chaff CC presents a value an order of magnitude higher than the others. Except for coffee chaff, it can be noticed that increasing the flow resistance also increases the porosity, that should be influenced by the presence of glue; in fact, for these four samples, the percentage of glue used (ELTs granulate 5%, cork 6%, rice husk 2.4%) is small and the porosity increases with this amount (minimum value is obtained for RH). When compared to the samples industrially manufactured, flow resistance values are lower while porosity values are higher, due to the increase of glue amount (13–21%) and the compression during the production, that caused a partial occlusion of the interconnected pores. Tortuosity values, calculated with the Berryman formula, increase with decreasing porosity. RH shows a low value (1.33), comparable with the ones of COR and ELT (1.28 and 1.20), while higher values (in the 1.74–1.85 range) are found for WP1, WP2, and WP3.

3.3. Acoustic absorption properties

In order to provide complete information about the most innovative material among the investigated ones (rice husk), a characterization considering the loose material for different thicknesses was performed and compared with the glued one (Fig. 6). The loose material in general presents lower absorption coefficient values than the glued one; as expected, the maximum peak value shifts to lower frequencies and a second peak appears when thickness increases. The maximum values are about 0.74 and 0.91 measured respectively at 1700 and 5300 Hz for the maximum thickness of 3.5 cm.

The comparison between the loose material and the glued sample with the same thickness (1.5 cm) shows that the acoustic behaviour of the glued rice husk sample is better at low-mean frequencies (up to 4000 Hz), the maximum value is higher (0.87) and it is obtained at a lower frequency (2600 Hz instead of about 3500 Hz).The acoustic experimental campaign was carried out on the other six panels (COR, ELT, CC, WP1, WP2, WP3), whose thicknesses are different, varying in the 1–5 cm range.

Table 6
Air-flow resistance, porosity, and tortuosity values for the investigated samples.

Sample	Flow resistance [Pa s/m^3]	Porosity [%]	Tortuosity [–]
RH	**11,700**	**59.7**	**1.33**
COR	18,450	64.2	1.28
ELT	20,200	71.4	1.20
CC	335,658	45.1	1.61
WP1	899,583	25.7	1.74
WP2	742,477	14.7	1.85
WP3	25,538	15.9	1.84

Fig. 7 shows the absorption coefficient trends for all the samples. RH, COR, ELT and CC present similar trends and good absorption performances, in the 0.4–0.99 range for frequencies higher than 1600 Hz. Only coffee chaff panel has a lower peak value shifted towards the low frequencies (about 0.57 at 900 Hz). The peak values are reached at the frequency of 2700 Hz for COR, ELT, and CC and the maximum value is obtained for the cork scraps (0.99), the minimum for the rice husk sample (0.87). Above 3600 Hz the trends are different: the rice husk sample has higher values than cork scraps and ELTs granulates.

Different trends were obtained for the waste paper samples (WP1, WP2, and WP3). WP1 and WP2 have similar acoustic behaviour with a maximum peak value of about 0.7 obtained around 1600 Hz; panel WP3 has an increasing trend that reaches 0.93–0.98 at frequencies higher than 2400 Hz. Anyway, in this case, the thickness of the sample is the highest one (50 mm).

In general, for a porous material, a high value of porosity is synonymous of good sound absorption; it can be observed that RH, COR, and ELT, which are characterized by higher porosity values, have the best sound absorption behaviour; only the WP3 trend differs from the others mentioned above (15.9% of porosity but a mean value of the sound absorption coefficient of 0.59), probably due to the different production process (compression phase).

3.4. Life cycle analysis

As described in the paragraph 2.5, the environmental impact of the rice husk panel is evaluated and compared with the one of the others recycled materials basing on three different functional units, in order to evaluate the environmental performance caused by the production process, but also to relate the impacts to the applications in the building sector, as sound absorbers and thermal insulating materials.

In Fig. 8 the environmental impact values in terms of GWP and CED categories are shown for the all the investigated panels, connected to the production of 1 m^2 of panel.

It can be noticed that the production of the panels made by coproduct of agrifood chains, such as rice husk and coffee chaff, determines the lowest GWP values (respectively 1.11 and 0.56 kg CO_{2eq}/m^2), because they are already available for reuse without further processing.

Other waste materials, as cork scraps and end life tires, are characterized by slightly high values of GWP and CED, due to long distance to the production site for cork scraps (Sardinia) and to additional crushing and grinding treatments necessary for the reuse of end life tires.

Among the waste paper based panels, the best environmental performance is obtained for panel WP3, made up of wool scraps and recycled paper, thanks to the lower amount of material required and density; the panel WP1 causes a very high energy consumption and GHG emissions due to the presence of polyethylene fibers material, which requires several treatment before use and the higher density of the panels when compared to the others.

From this first life cycle assessment, it can be noticed that the rice husk panel (RH) allows to obtain an emission saving ranging from 64 to 86% with respect to WP1, WP2, and WP3 panels. Only coffee chaff panel (CC) has a better performance, with a maximum reduction of 93%.

CED values of RH are a little bit higher than the ones of CC, WP2, and WP3, but significantly lower (more than 50%) with respect to data related to COR, ELT, and WP1.

In order to evaluate and to compare the environmental impacts basing on acoustic properties of the panels, 1 absorption unit (A) was considered as functional unit, as the corresponding area (m^2) of the absorber panel necessary to guarantee 1 A.

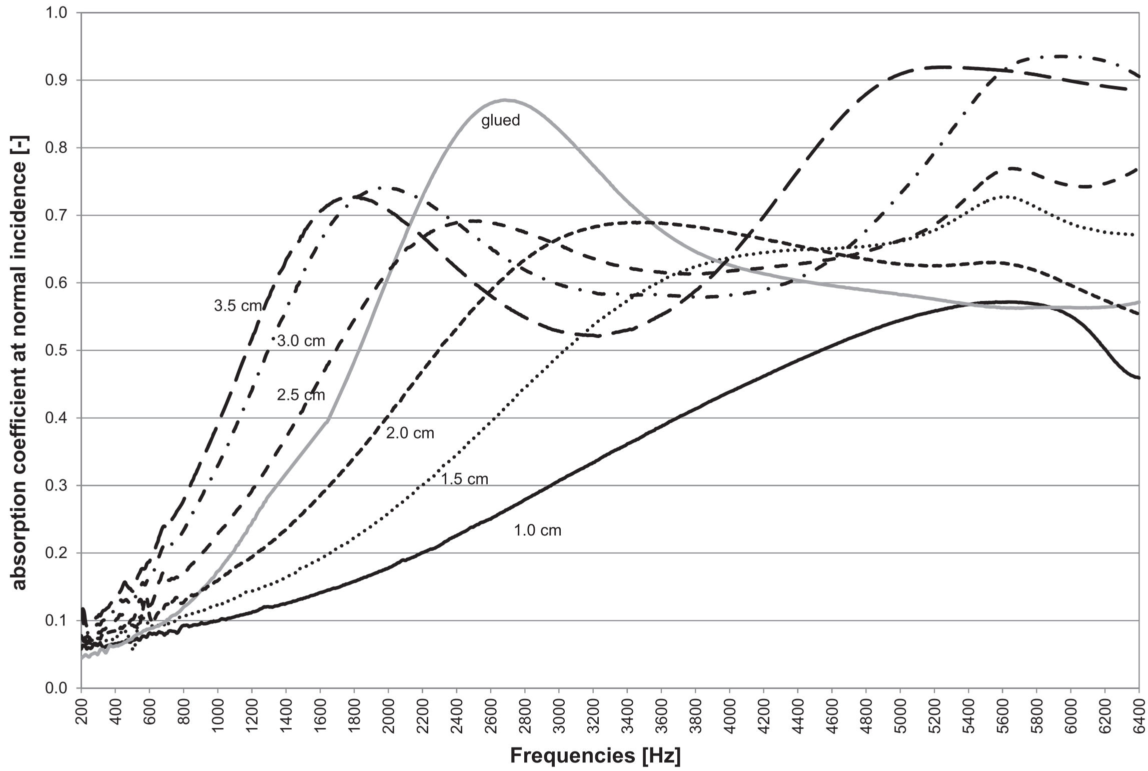


Fig. 6. Sound absorption coefficient trends of the loose rice husks by varying the thickness.

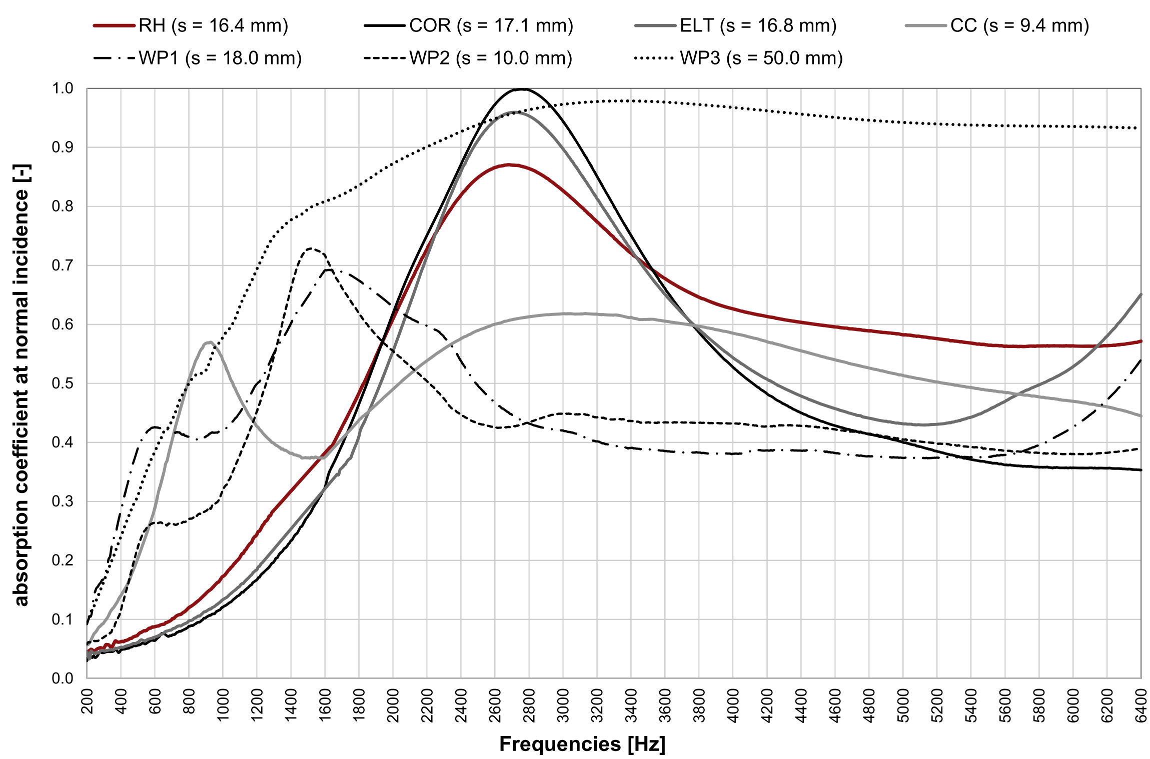


Fig. 7. Sound absorption coefficient trends for all the glued sample.

In Table 7, the value of α_m (the arithmetic average, rounded to the nearest multiple of 0.01, of the absorption coefficients determined at the one octave band centre frequencies of 250, 500, 1000, 2000 and 4000 Hz and the corresponding areas for 1 unit absorption are shown.

The α_m values range around 0.29–0.39, except for the sample WP3 that results the best sound absorption panel, with a value of 0.59.

In addition a comparison based on thermal performance of the panels is performed, and another specific functional unit is defined,

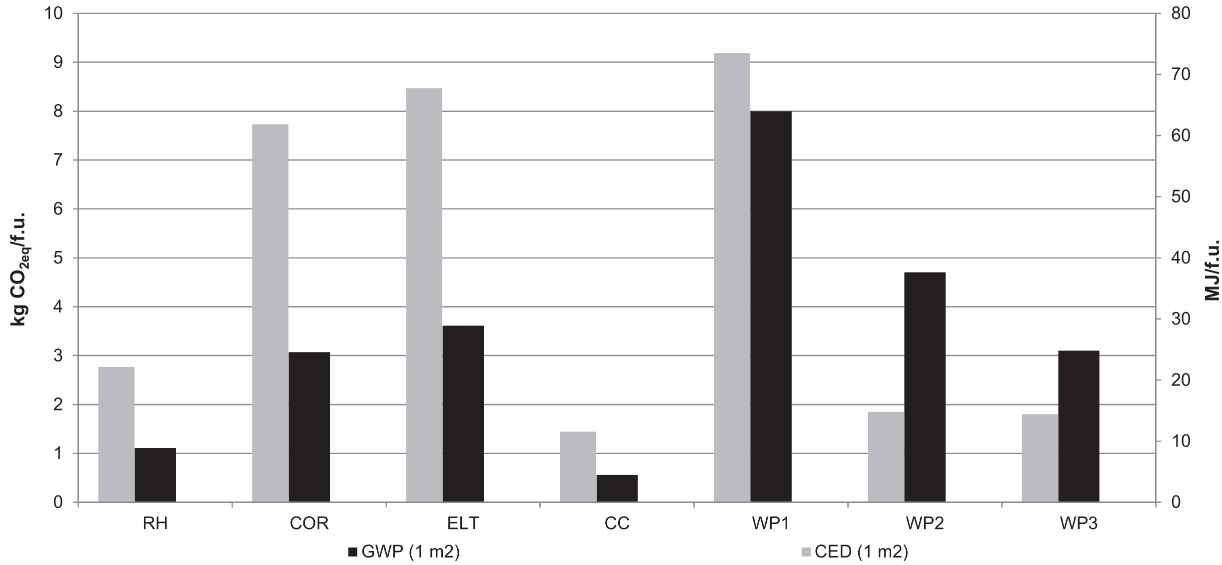


Fig. 8. GWP (kg CO_{2eq}) and CED (MJ) for the production of 1 m^2 of the investigated panels.

Table 7
Functional unit for comparison in terms of sound absorption.

Panels	α_m	1 A (m^2)
RH	**0.33**	**3.03**
COR	0.29	3.45
ELT	0.30	3.33
CC	0.38	2.63
WP1	0.39	2.56
WP2	0.32	3.13
WP3	0.59	1.69

Table 8
The functional unit (kg) needed to provide a thermal resistance of 1 m^2 K/W.

Sample	λ_i [W/mK]	R_i [m^2K/W]	ρ [kg/m^3]	f.u. [kg]
RH	**0.070**	**0.58**	**170**	**11.90**
COR	0.055	0.83	195	10.73
ELT	0.135	0.30	550	74.25
CC	0.076	0.39	350	26.60
WP1	0.038	0.47	605	22.99
WP2	0.036	0.28	646	23.26
WP3	0.050	1.11	110	5.50

as already explained at paragraph 2.5. In Table 8, the functional unit for thermal application comparison is calculated basing on Eq. (5).

The investigated panels present a value of mass necessary to obtain 1 m^2 K/W of thermal resistance of 5–26 kg, except for end life tires (around 74 kg), characterized by the highest value of the thermal conductivity.

In Fig. 9 the environmental impacts in terms of GWP and CED categories are shown for the all the investigated panels, connected to the application as absorber panel (f.u. = 1 A) and thermal insulating material (f.u. = 1 R).

Taking as a reference the sound absorption unit (1A), rice husk and coffee chaff panels are the best acoustic absorption solutions, considering the life cycle impacts, thanks to the neglected impacts due to their origin from other manufacturing processing.

The high values of GWP and CED for COR and ELT panels are related to the treatment for processing the materials and to the poor behaviour in sound absorption.

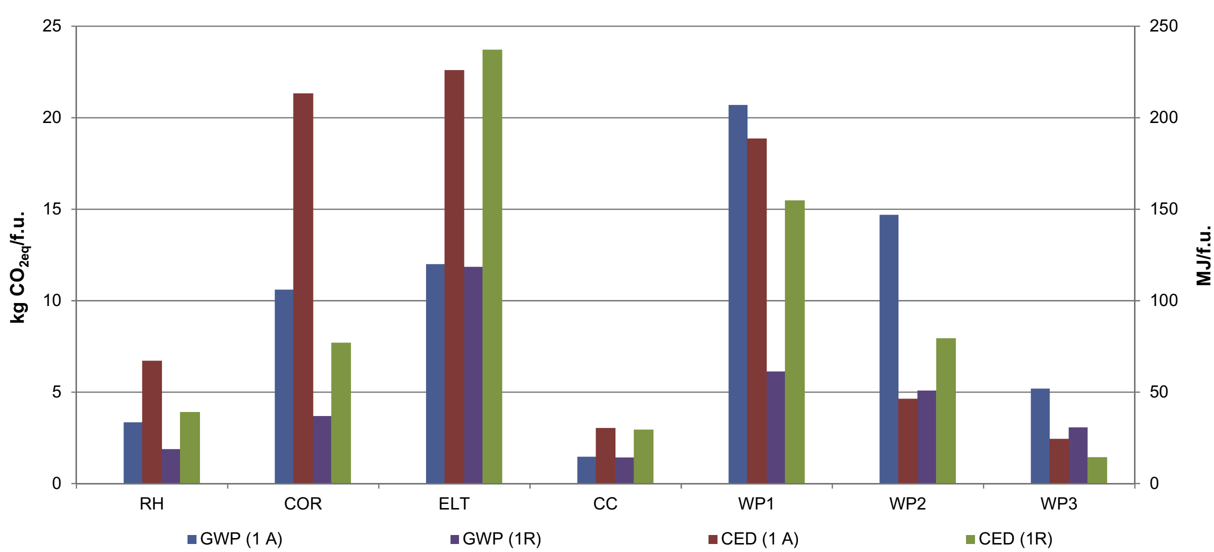


Fig. 9. GWP (kg CO_{2eq}) and CED (MJ) for acoustic and thermal comparison.

The recycled materials from agricultural processes (RH and CC) allow to obtain a higher emission saving than waste paper-based materials.

It can be noticed that only the panel made of waste paper and wool scraps (WP3) allows to reach a similar performance of rice husk and coffee chaff, thanks to the high absorption coefficient of the wool.

The comparison based on thermal insulation capability of the panels shows similar performance for all the panels, except ELT: considering the thermal resistance, the GHG emissions and CED range from 1.4 to 6.1 kg CO_{2eq} and 14–155 MJ per functional unit respectively.

In general, the best solutions for thermal application are the RH, CC, and WP3 panels, characterized by lower environmental impacts and best thermal insulation performance. Also cork panel COR becomes an interesting choice for thermal insulation, thanks to its low value of thermal conductivity.

4. Summary and conclusion

New techniques aiming at controlling and reducing the environmental impacts of the construction chain have become important, in particular concerning the building materials. In this scenario, the use of recycled waste materials as building components can be a good solution. In the present paper a rice husk (RH) panel was fabricated and studied from different perspectives and its thermal, acoustic, and environmental performance were compared with the ones of traditional and innovative boards made with the same construction technique.

The acoustic, thermal, and environmental performances were evaluated in order to propose their application as insulating and acoustic panels for the building sector: in particular the attention is focused on rice husk, a non-conventional material never used for building application industry.

The thermal conductivity of the rice husk panel, evaluated by small Hot-Box apparatus, is 0.07 W/mK and it is in the same order of magnitude of many traditional insulating systems, such as cork scraps panels (0.055 W/mK); other panels made of waste paper (WP1 and WP2) investigated in precious works, are characterized by very low values of λ (0.038 W/mK and 0.036 W/mK, respectively) and result as innovative and interesting thermal insulation solutions.

In order to evaluate the acoustic performance, the absorption coefficient was tested in the range 200–6400 Hz by means of the impedance tube method. Rice husk, characterized both as loose and glued material, presents absorption coefficient peak values in the 0.70–0.84 range, depending on its thickness; glued panels present higher values than loose material. The other panels present acoustic absorption potential comparable to the traditional ones (peak values of about 0.61–0.99), but the best absorption coefficient trend is obtained for wool scraps and waste paper panels.

A Life Cycle analysis was finally performed, in compliance with ISO 14040 series requirements. The aim was the assessment and definition of the cumulative energy demand (Embodied Energy) and the global warming potential (GWP 100 years) as environmental impact indexes associated to the panels' production.

Considering the production process (functional unit f.u. = 1 m^2), the best environmental performance was obtained for rice husk (1.11 kg CO_{2eq}/m^2) and coffee chaff (0.56 kg CO_{2eq}/m^2) panels, due to the neglecting impacts of their reuse as coproducts of other chains.

Basing on acoustic and thermal performance, the environmental impact study shows that rice husk and coffee chaff panels are the best acoustic absorption solutions and only the panel made of waste paper and wool scraps (WP3) allows to reach a similar performance, thanks to the high absorption coefficient of wool. From thermal insulation comparison, a good performance of all the panels can be noticed, except ELT: considering the thermal resistance value, the environmental impacts and energy consumptions are in the 1.4–6.1 kg CO_{2eq} range and 14–155 MJ range per functional unit for GWP and CED respectively. The results lead to the conclusion that the environmental benefits from using by-products to realize new innovative materials is related to the neglected impacts for their origin from other manufacturing processing. The comparison confirms that the innovative rice husk glued panel is an interesting solution for sound absorption and thermal insulation applications, thanks to a good behaviour at mean-high sound wave frequencies, a good value of thermal resistance, and a very low environmental impact in the production phase.

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References

[1] G.A. Blengini, T.D. Carlo, The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings, Energy Build. 42 (2010) 869–880.
[2] B. Peuportier, P. Thiers, A. Guiavarch, Eco-design of buildings using thermal simulation and life cycle assessment, J Clean. Prod. 39 (2012) 73–78.
[3] P. Karami, N. Al-Ayish, K. Gudmundsson, A comparative study of the environmental impact of Swedish residential buildings with vacuum insulation panels, Energy Build. 109 (2015) 183–194.
[4] A.M. Papadopoulos, State of the art in thermal insulation materials and aims for future developments, Energy Build. 37 (2005) 77–86.
[5] A.D. La Rosa, A. Recca, A. Gagliano, J. Summerscales, A. Latteri, G. Cozzo, et al., Environmental impacts and thermal insulation performance of innovative composite solutions for building applications, Constr. Build. Mater. 55 (2014) 406–414.
[6] N. Pargana, M.D. Pinheiro, J.D. Silvestre, J. de Brito, Comparative environmental life cycle assessment of thermal insulation materials of buildings, Energy Build. 82 (2014) 466–468.
[7] S.M. Batouli, Y. Zhu, M. Nar, N.A. D'Souza, Environmental performance of kenaf-fiber reinforced polyurethane: a life cycle assessment approach, J. Clean. Prod. 66 (2014) 164–173.
[8] P. Ricciardi, E. Belloni, F. Cotana, Innovative panels with recycled materials: thermal and acoustic performance and life cycle assessment, Appl. Energy 134 (2014) 150–162.
[9] H. Koruk, G. Genc, Investigation of the acoustic properties of bioluffa fiber and composite materials, Mater. Lett. 157 (2015) 166–168.
[10] M. Volf, J. Diviš, F. Havlík, Thermal, moisture and biological behaviour of natural insulating materials, Energy Procedia 78 (2015) 1599–1604.
[11] FAO Official data, http://faostat3.fao.org/; 2017 [last access 12.12.17].
[12] T.N.T. Izhar, L.M. Deraman, W.N. Ibrahim, N.A. Lutpi, Investigation of noise reduction coefficient of organic material as indoor noise reduction panel geopolymer and green technology materials, Trans. Tech. Publications 803 (2014) 317–324.
[13] S. Sakamoto, Y. Takauchi, K. Yanagimoto, S. Watanabe, Study for sound absorbing materials of biomass tubule etc. (measured result for rice straw, rice husks, and buckwheat husks), J. Environ. Eng. 6 (2011) 352–364.
[14] D.W. Yarbrough, K.E. Wikes, P.A. Olivier, R.S. Graves, A. Vohra, Apparent thermalconductivity data and related information for rice hulls and crushed pecan shells, Therm. Cond. 27 (2005) 222–230.
[15] H.S. Yang, D.J. Kim, H.-J. Kim, Rice straw–wood particle composite for sound absorbing wooden construction materials, Bioresour. Technol. 86 (2003) 117–121.
[16] S.K. Tulashie, F. Kotoka, D. Mensah, A.K. Kwablah, Investigation of the compressive strength of pit sand, and sea sand mortar prisms produced with rice husk ash as additive, Constr. Build. Mater. 151 (2017) 383–387.
[17] H. Keskin, M. Kucuktvek, M. Guru, The potential of poppy (Papaver somniferum Linnaeus) husk for manufacturing wood-based particleboards, Constr. Build. Mater. 95 (2015) 224–231.
[18] J. Rives, I. Fernandez-Rodriguez, J. Rieradevall, X. Gabarrell, Environmental analysis of raw cork extraction in cork oak forests in southern Europe (Catalonia e Spain), J. Environ. Manage 110 (2012) 236–245.
[19] Cork Oak Forest, http://www.giarasardegna.it/en/content/cork-oak-forest; 2018 [last access 16.01.18].

[20] E.M. Fernandes, V.M. Correlo, J.A.M. Chagas, J.F. Mano, L. Rui, R.L. Reis, Properties of new cork–polymer composites: advantages and drawbacks as compared with commercially available fibreboard materials, Compos. Struct. 93 (2002) 3120–3129.
[21] R. Manderulo-Sanz, J.R. Barrigon-Morillas, V. Gomez, Escobar, Acoustical performance of loose cork granulates, Eur. J. Wood Prod. 72 (2014) 321–330.
[22] G. Vasconcelos, P.B. Lourenco, A. Camoes, A. Martins, S. Cunha, Evaluation of the performance of recycled textile fibres in the mechanical behavior of a gypsum and cork composite material, Cem. and Concr. Composite 58 (2015) 29–39.
[23] A.E. Tiuc, O. Vasile, T. Gabor, Determination of antivibrational and acoustical properties of some materials made from recycled rubber particles and sawdust, Department Enviromental Engineering and Sustainable Development Entrepreneurship, Technical University of Cluj-Napoca, Romania, Department of Mechanics Politechnica of Bucharest, Romania, RJAV vol. XI issue 1/2014.
[24] World wide web, http://www.ford.com/default.asp?pageid=73 [last access 12.12.17].
[25] A. Santini, L. Morselli, F. Passarini, I. Vassura, S. Di Carlo, F. Bonino, End-of-life vehicles management: italian material and energy recovery efficiency, Waste Manage. 31 (2011) 489–494.
[26] R. Maderuelo-Sanz, M. Martin-Castizo, R. Vilchez-Gomez, the performance of resilient layer made from recycled fluff for impact noise reduction, Appl. Acoustics 72 (2011) 823–828.
[27] K.V. Horoshenkov, M.J. Swift, The effect of consolidation on the acoustic properties of loose rubber granulates, Appl. Acoustics 62 (2001) 665–690.
[28] R. Maderuelo-Sanz, A. Nadal-Gisbert, J. Crespo-Amoros, F. Parrez-Garcia, A novel sound absorber with recycled fibers coming from end of life tires, Appl. Acoustics 73 (2012) 402–408.
[29] N.D. Freedman, Y. Park, C.C. Abnet, A.R. Hollenbeck, R. Sinha, Association of coffee drinking with total and cause-specific mortality, N. Engl. J. Med. 366 (2012) 1891–1904.
[30] L. Bresciani, L. Calani, R. Bruni, F. Brighenti, D. Del Rio, Phenolic composition, caffeine content and antioxidant capacity of coffee silverskin, Food Res. Int. 61 (2014) 196–201.
[31] P. Ricciardi, F. Torchia, E. Belloni, E. Lascaro, C. Buratti, Environmental characterisation of coffee chaff, a new recycled material for building applications, Constr. Build. Mater. 147 (2017) 185–193.
[32] C. Buratti, E. Belloni, E. Lascaro, G.A. Lopez, P. Ricciardi, Sustainable panels with recycled materials for building applications: environmental and acoustic characterization, Energy Procedia 101 (2016) 972–979.
[33] U. Berardi, G. Iannace, Acoustic characterization of natural fibers for sound absorption applications, Build. Environ. 94 (2015) 840–852.
[34] J.-O. Yeon, K.-W. Kim, K.-S. Yang, J.-M. King, M.-J. King, Physical properties of cellulose sound absorbers produced using recycled paper, Constr. Build. Mater. 70 (2014) 494–500.
[35] C. Buratti, E. Belloni, L. Lunghi, M. Barbanera, 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 (2016) 47.
[36] ISO 10534-1, Acoustics –Determinations of sound absorption coefficient and impedance tube Part 1: methods using standing wave ratio, 1996.
[37] ISO 10534-2, Acoustics –Determinations of sound absorption coefficient and impedance tubes Part 2: Transfer function method, 1998.
[38] ISO14040, Environmental Management – Life Cycle Assessment – Principles and Framework, 2006.
[39] ISO14044, Environmental Management – Life Cycle Assessment – Requirements and Guidelines, 2006.
[40] A. Kumar, K. Mohanta, D. Kumar, O. Parkash, Properties and Industrial Applications of Rice husk: A review, International Journal of Emerging Technology and Advanced Engineering Website: www.ijetae.com (ISSN 2250-2459, Volume 2, Issue 10, October 2012).
[41] M. Sarangi, S. Bhattacharyya, R.C. Behera, Rice Effect of temperature on morphology and phase transformations of nanocrystalline silica obtained from rice husk, Phase Transitions 82 (5) (2009) 377–386.
[42] ISO 9053, Acoustics – Materials for acoustical applications – Determination of airflow resistance (2011).
[43] P. Leclaire, O. Umnova, K. Horoshenkov, L. Maillet, Porosity measurement by comparison of air volumes, Rev. Sci. Instrum. 74 (3) (2003) 1366–1370.
[44] O. Umnova, K. Attenborough, H.C. Shin, A. Cummings, Deduction of tortuosity and porosity from acoustic reflection and transmission measurements of thick samples of rigid-porous materials, Appl. Acoustics 66 (6) (2004) 607–624.
[45] E. Moretti, E. Belloni, F. Agosti, Innovative mineral fiber insulation panels for buildings: thermal and acoustic characterization, Appl. Energy 169 (2016) 421–432.
[46] C. Buratti, E. Moretti, E. Belloni, F. Agosti, Development of innovative aerogel based plasters: preliminary thermal and acoustic performance evaluation, Sustainability 6 (2014) 5839–5852.
[47] N. Huberman, D. Pearlmutter, A life-cycle energy analysis of building materials in the Negev desert, Energy Build. 40 (2008) 837–848.
[48] A. Patnaik, M. Mvubu, S. Muniyasamy, A. Botha, R.D. Anandjiwala, Thermal and sound insulation materials from waste wool and recycled polyester fibers and their biodegradation studies, Energy Build. 92 (2015) 161–169.
[49] ISO 8990. Thermal Insulation – Determination of Steady-State Thermal Transmission Properties – Calibrated and Guarded Hot Box, 1994.
[50] C. Buratti, F. Merli, E. Moretti, Aerogel-based materials for building applications: influence of granule size on thermal and acoustic performance, Energy Build. 152 (2017) 472–482.
[51] JCGM 100:2008 – Evaluation of measurement data – Guide to the expression of uncertainty in measurement.