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Thermo-acoustic building insulation materials fabricated with recycled fibers – Jute, Wool and Loofah

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ABSTRACT

Reducing the environmental impact of construction, one of the most polluting industrial sectors, is essential to combat the climate crisis and, for this purpose, we need to start from natural, recyclable and sustainable materials. In this research, panels fabricated with jute and wool fibers, recycled respectively from jute bags used (end-life) for packaging coffee beans and from old (end-life) mattresses, and panels fabricated with a loofah-clay mix were realized and characterized. Comparative analyses were carried out considering in particular insulating characteristics in terms of thermal conductivity and acoustic performance.

The thermal conductivity values obtained for jute fibers panels are always included in the upper range of results available for wool fiber with similar density (about 20 kg/m^3), but always the lower range of results available for jute-polyester-polypropylene sandwich composite panels. The results obtained for products with clay are obviously strongly dependent on the percentage of binder (clay) in the mix, the increase of which leads to an increase in density, negatively influencing the results obtained. Also, if from the acoustic point of view, it is not possible to add the contribution of the single layers, the noise insulation calculated for the different materials under test has shown for the single layer the good property to break down the noise.

1. Introduction

Global warming due to the rise in the atmospheric temperature is one of the main concerns of the global community. As the climate change not only directly affect the ecosystems but also challenge the existence of mankind. The concentration of greenhouse gases in the atmosphere, particularly CO_2 is responsible for greenhouse effect by rising the global near-surface air temperature [1].

The Construction and Building (C&B) sector alone accountable for about 39 % of the total CO_2 emission and responsible for 36 % of the total energy consumption, globally [2]. While these numbers are 36 % and 40 %, respectively in European Union (EU) context [3,4]. Notably out of total energy consumption in EU, around 50 % primarily used for HVAC and water heating [5].

According to the existing ambition, the key targets of the 2030 climate and energy framework is to (i) reduce the greenhouse gas emissions (from 1990 levels) by 40 %, (ii) to reach the renewable energy share minimum by 32 % and (iii) the energy efficiency improvement at least by 32.5 % [5,6].

As well, to accomplish the objectives of the Paris agreement [7] and to achieve climate-neutral economy by 2050 (i.e. an economy with net-zero greenhouse gas emissions) [8], the EU has adopted various policies. Notably the Nearly zero-emission building (NZEB [9,10]), whereas in December 2021 it has proposed for Zero-emission building (ZEB), therefore all new buildings should adopt ZEB by 1 January 2030 and public sector buildings (occupied or owned) by 1 January 2027 [11]. Consequently, the countries come under EU are committed to optimize the energy consumption and to reduce the greenhouse gases emission. As highlighted in [12–15] one of the way to achieve these goals is proper thermal insulation and this can help to save near-about 65 % of the total building energy consumption.

The man-made synthetic organic and inorganic fibers [16,17] predominantly are used in the C&B sector for thermal and structural retrofitting and reinforcement.

About 35 %, 20 % and 34 % of the total market shares of thermal insulation materials is held by glass wool, stone wool and EPS&XPS,

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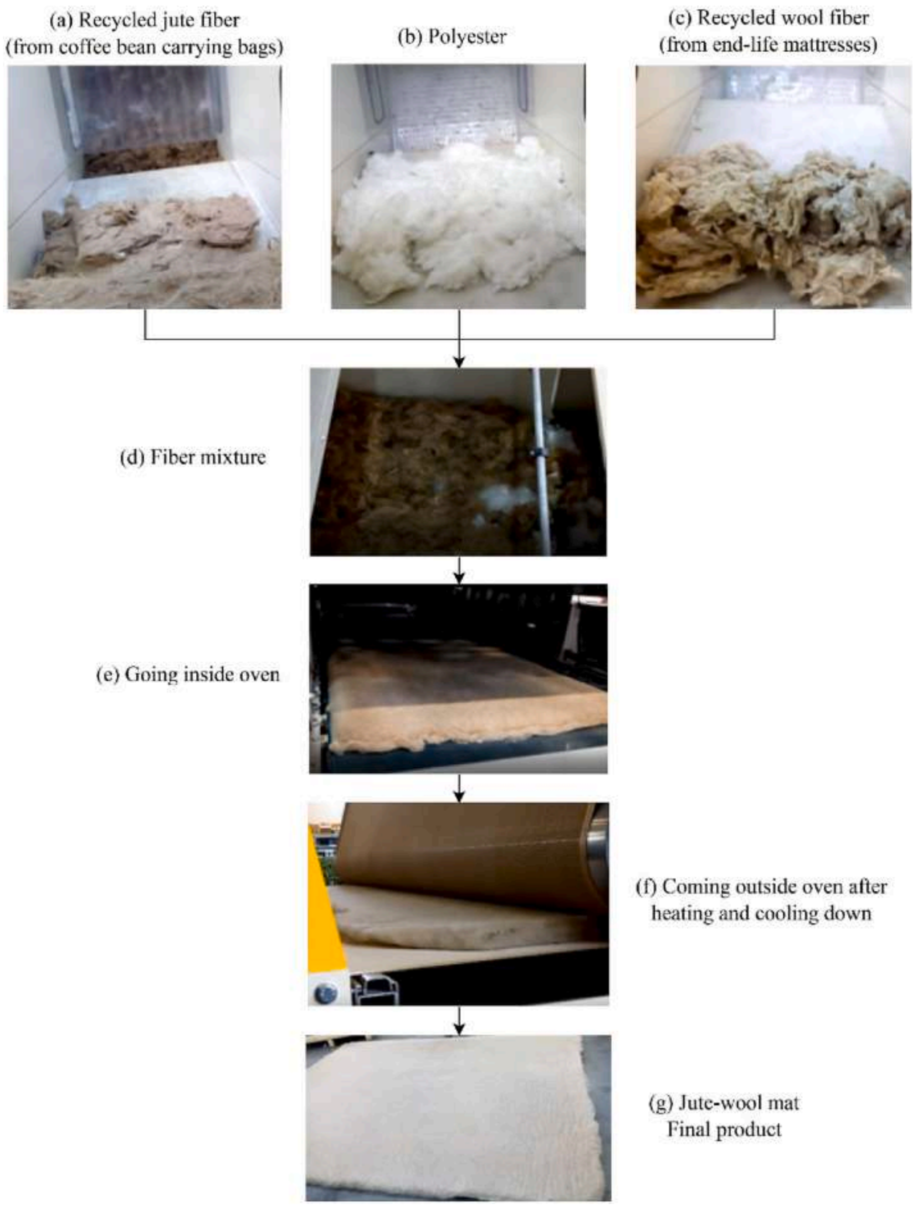


Fig. 1. Schematic diagram of the SW samples preparation.

Table 1
Amount used in the mixture.

Main insulating materials		Binding material (Bi-component)	Sample density	
Jute fiber collected from transportation jute bags	Wool collected from old mattresses	polyester + Co–polyester	Mean [kg/m^3]	Co.V [%]
40 %	40 %	20 %	20.14	7.12 %

Co.V = Coefficient of variation

respectively materials [18].

In inorganic fibers, the chemicals used can be irritants [19] and sometimes known to be harmful to human health [20] and responsible for air pollution from energy use during production [19].

According to [19], the chemicals used in the organic insulation materials might cause some health issue to some individuals, and also responsible known for concerning environmental impacts like, pentane emission which contribute to smog, ozone depletion, global warming etc.

Furthermore, the raw material sources of these materials are non-renewable and non-organic, and the same products are not easy to recycle at the end of their life cycle [21–23].

The innovative and recycled applications of different natural fibers in various forms in the C&B sector can be found in the literature, it is enough to mention flex [24], banana [25], coconut coir [26,27], sisal [28], date palm [29], hemp [30], sheep wool [31,32], jute [33,34], oil palm [35], straw [36], wood-wool [37], kenaf [38] or posidonia [39]. While the use and application of wool fiber (from animal origin) mainly can be found as thermo-acoustic insulation material [40,41], other experiments were conducted using them in cement matrix materials (mortar or plaster) [31,42], concrete composite [43] and reinforce concrete and carbon fiber precursor [44]. From the environmental impact point of view, the strategic importance of subsidies provided by local governments to incentivize waste prevention and reduce waste end-treatment should be underlined. It is recognized that the impact of subsidy schemes, when they are a function of the results obtained, become closely related to market demand and fixed cost ratios. Conversely, a fixed cost grant for recyclers results in a higher recycling

Fig. 2. Insulation panel made of recycled jute and wool fiber.

Table 2
Amount of ingredients used in the mixture for Jute fiber panels.

Sample nomenclature	Main insulating materials	Binding material		Additional plastering material applied only on one side	Sample density	
	Raw jute fiber	Clay	Water	Clay	Mean [kg/m^3]	Co.V [%]
JC	14.0 %	48.5 %	37.5 %	x	786.81	2.31
JCP	12.0 %	50.0 %	38.0 %	2 mm	1054.43	2.45

Co.V = Coefficient of variation

rate, better environmental and social welfare performance [45].

In this research the authors focus the attention on two products of vegetable origin, very different in terms of diffusion on the market, but with wide possibilities of use in the building insulation sector: jute and loofah fibers. Interestingly, the jute fibers (JF) hold the second spot among all produced fibers [46], resulting it a cheap product and widely available in market. Like all other fibers, JF too has some advantages and disadvantages. JF is recyclable and biodegradable. Moreover, energy consumption needed for its (and sub-products) production process is comparatively very low with respect to other fibers [39,47]. JF's proven insulating property as well as its mechanical and physical strength, brings wider attraction to develop more sustainable building materials. On the other hand, it is necessary to highlight that when it comes into contact with water, it's moisture absorbability rises and strength reduces [47,48]. Various application of JF can be found in the literatures mainly in raw form, composite form or hybrid form, for example crude earth brick [49], burnt earth brick [50], retrofitting concrete [51–53], composite mortar [53,54], epoxy composite [55] and FRP [56]. Whereas use of recycle jute fibers in insulation panel and composite block are mentioned in Majumder et al. [57] and Ferrandez-García et al. [58], respectively. Loofah cylindrica is mainly grown for its fruit in the region around South and Southeast Asia, and consumed as vegetables when they are young. The fiber derived from mature and dry fruits has various uses and predominantly used as bathroom and kitchen sponges, washing and cleaning materials and sound proofing materials [59]. Whereas loofah fiber's mechanical properties, and information related its composites can be found in [60] and [61,62], respectively.

This experimental research work emphasizes the possibility to recycle end-life /waste materials like jute fibers (collected from end life jute coffee bean carrying bags) and wool fibers (collected from end-life old mattresses) and use these refusals to create new building insulation material (panel). The residual raw jute fibers were collected form the masonry retrofitting process and has been used to fabricate two types of composite insulation block materials, one of which applied with clay plaster. Whereas loofah fibers used during this experiment were the residual/waste from production process and donated by a local industry, which produces gloves, mittens and sponges for bath and kitchens.

According to the European Agency for the Environment [63], the main noise source to which exposed the large number of people is caused by the vehicular trafficking present inside and outside the cities. For this reason, one of the fundamental aspects required of the new buildings or the old buildings that are renovated is that of giving a good acoustic insulation of the facade. Internationally, the used parameters to describe acoustic insulation are different and are based on equations that usually take into account numerous aspects including the form of the facade. The international standard ISO 12354-1 [64] is widely used during the design phase to evaluate the noise insulation offered by the individual building components.

In this work the performance in terms of thermal conductivity and noise insulation power of eco-sustainable materials, to be used in the design of building components was investigated.

Three types of materials were used: "Jute", "Wool" and "Loofah", all recycled from other industrial and research activities. They were prepared in order to directly realize insulating panels (Jute with wool and polyester) or to be mixed in other standard building materials using clay as binder matrix. The thermal properties were experimentally determined using a Heat Flow Meter (HFM) instrument, according to ISO 8301 [65]. The results were compared with the values of similar

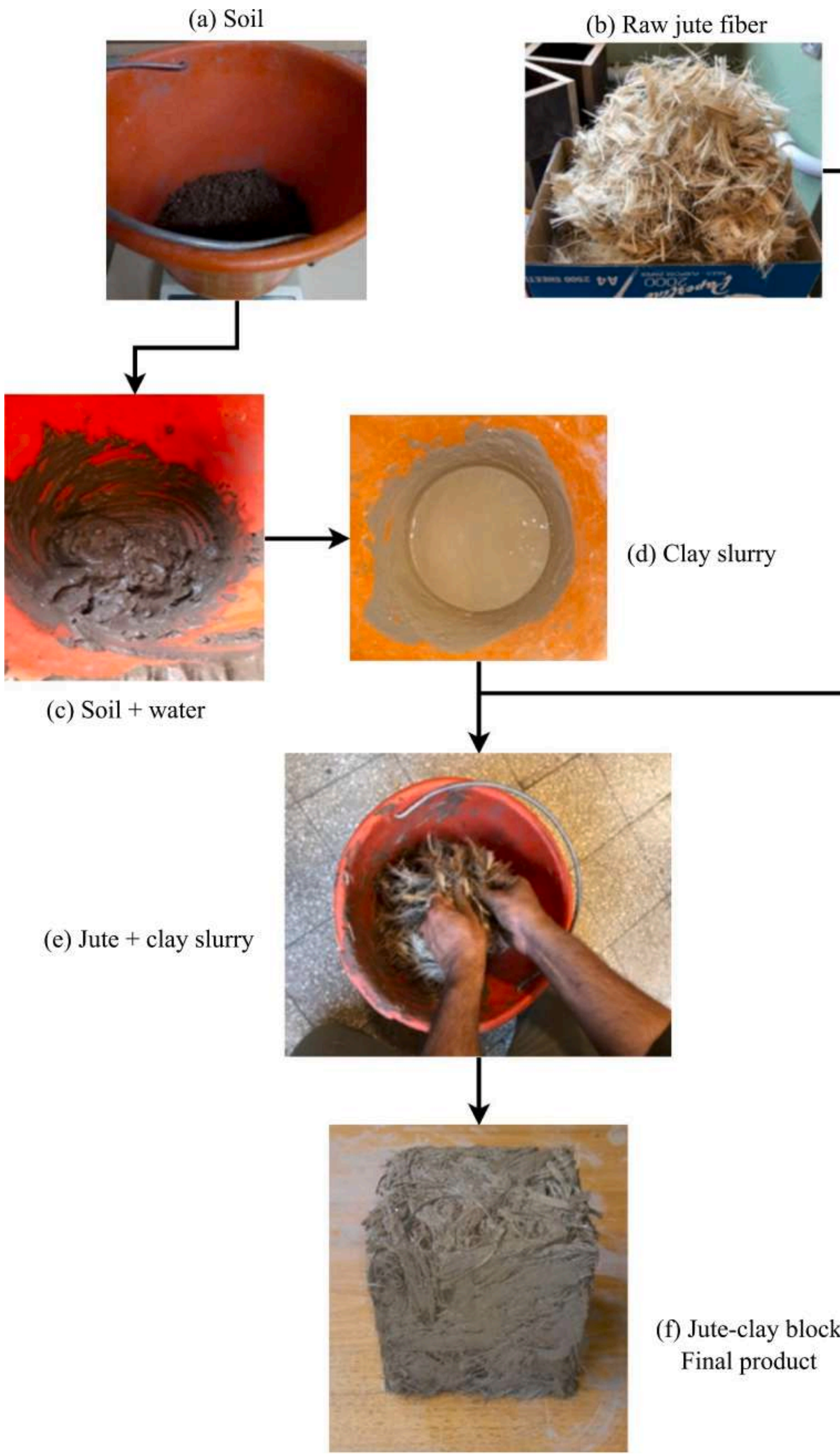


Fig. 3. Schematic diagram of the SC and SCP samples preparation.

(b)

Fig. 4. (a) Insulation material: Jute fiber and clay used as binding material, (b) Insulation material: jute fiber and clay used as binding and plaster materials.

products available in literature highlighting the possible differences in terms of mixing ratio. The acoustic insulation capacity was theoretically evaluated according to [64], highlighting the contribution of the superficial mass of the layer.

2. Material and methods

2.1. Sample materials

Three types of recycled materials were used in the study: jute, wool and loofah. In particular, jute and wool, in equal quantities (40 %), were mixed with polyester (20 %) to realize insulating panels having density about 20 kg/m^3. Jute or loofah were mixed in different quantities with clay to improve thermally and acoustically standard building materials. The samples had a density variable from 800 to 1000 kg/m^3 for jute and about 400 kg/m^3 for loofah.

2.1.1. Jute-wool fiber insulation panels

These insulation panels were prepared by using recycled jute and wool fibers fused with bicomponent (two types of polyester). The jute fibers have been collected from coffee bean carrying (end-life) jute bags. Whereas wool fibers have been collected from old used (end-life) mattresses (Fig. 1). Equal quantity (i.e., 40 %) of both recycled fibers has been used in the mixture. While four times less quantity i.e., about 20 % of bicomponent has been added in the mixture with respect to the total fiber mass (see Table 1). The bicomponent has been collected in fiber form and in mixture it acts as binder and provides rigidity to the final product. The raw materials are provided by the industrial project partner.

These three materials were put into three different loading machines, and each of them has been equipped with its own weight measuring system. The loader and the carrying belt have been pre-set to synchronize, so as to drop the exact amount of fibers to have the mixture with exact ratio of each material. Thereafter the mixture passes through various stages in separate machines, to start with pre-mixing, followed by separator of the trapped air and dusts. Thereafter the mixture was re-mix again and the fibers and bi-component mixture was shoot into a machine the using a ventilator, in which the initial desired shape was provided, to have the panel. The fiber mixture with given shape pass through an oven with inside temperature of 160 °C. This thermal process is important to eliminate all impurities and to kill all remaining germs. But above all this heating cause melting of co-polyester (bicomponent) and the fibers are bound to provide a rigid form to the insulation panel. Then it goes through cooling process and comes out as final product as in Fig. 1. All these steps are computerized and respective machines has their own control system. The samples were made using equipment and technologies able to guarantee homogeneity in the mixture distribution of components and adequate repeatability in the final products. The carding process guarantees the absence of surface irregularities.

Several panels of surface area of 250x250 mm were cut randomly (see Fig. 2) from every corner of the original sheet and the density of the jute-wool fiber insulation panel was determined (see Table 1). The extent of density variability (σ = standard deviation) in relation to the mean (μ) of the population is expressed with the Coefficient of Variation (Co.V = σ/μ).

2.1.2. Jute fiber-clay composite insulation panel without (JC) and with clay plaster (JCP)

The mixture for JC and JCP were prepared following UNI EN 1015-2 [66] and using the similar mixture composition as in [56,57]. Being, these samples to be used particularly as insulation panel and not for structural purpose, the consistency of the mixtures (for JC and JCP) was considered to be acceptable as in Majumder et al. [57] and no shaking table tests have been conducted. The materials used and the mixture composition of these two types of samples have been listed in Table 2.

To prepare these composite insulation panels, the residual raw jute fibers were collected from another research activity performed on the masonry retrofitting process, at University of Cagliari. These jute fibers are mainly of *C. olitorius* origin. The fibers were cut randomly (Fig. 3b) without uniformity and with length vary from 5 mm to 40 mm. The soil (Fig. 3a) was collected from local quarry and has quasi black color. It inherent all types of impurities including small pebbles to big stones. Therefore, all unwanted materials have been separated and clay dust has been obtained. Thereafter by adding water, clay slurry was created (Fig. 3c). Later jute fibers were mixed to clay slurry with hand (Fig. 3f) to provide uniformity to the mixture, as fibers when come in contact with slurry have shown the tendency to form small balls [33]. Wooden molds of 100 × 100 × 100 mm^3 were used to prepare four samples of each type. At first half of the molds were filled and 25 S were applied. Thereafter after completely filling the molds another 25 S were applied. These was done to uniformly distribute the mixture inside the mold, and also to remove the trapped air bubble from the sample. The samples upper surfaces were leveled and left for two days inside a plastic airtight bag. Thereafter the samples were removed from the molds and left inside other plastic bags for another five days. Total after two plus five days, the samples were left outside for normal drying in room with quasi constant average temperature and average relative humidity of 22 °C and 65 %, respectively. Only in the case of JCP, a layer of clay plaster of 2 mm was applied, as in the Fig. 4b.

It should be noted that the samples were made following a manual procedure fruit of authors previous experience, which, even with due attention aimed at making the mixture obtained as homogeneous as possible, is not able to guarantee adequate repeatability for all the final products. However, the risk of a partially uneven surface caused by the lack of carding was minimized with the help of a suitable flat compression during the drying phase.

2.1.3. Loofah fiber-clay composite insulation panel (LC)

The LC insulation panels were prepared using loofah and clay. Both raw materials were collected locally. The loofah fibers (Fig. 5a) used in this case were scraps collected from a local farmer-artisan, uses loofa to produce kitchen and bathroom sponges and gloves. Whereas the thick red type of soil (Fig. 5b), chosen as the binder material, was collected directly by the authors. This type of soil has been chosen because it is known to be perfect for fiber mixture. The technique to prepare the panels was followed similar to that of straw-clay adobe bricks as in Achenza et al. [67].

To obtain finer and softer binder materials, the impurities like smaller pebbles and larger stones were separated from the soil, by crushing it in a muller and thereafter by sifting using a sieve to obtain fine clay dusts (Fig. 5c and d). At the same time the loofah fibers were chopped and washed (Fig. 5e and f). The clay-slurry (Fig. 5g) was prepared by adding adequate amount of water (Table 3). Thereafter the chopped loofah fiber and clay-slurry were mixed to fabricate the loofah-clay insulation panels (Fig. 5h). The loofah-clay panels were prepared

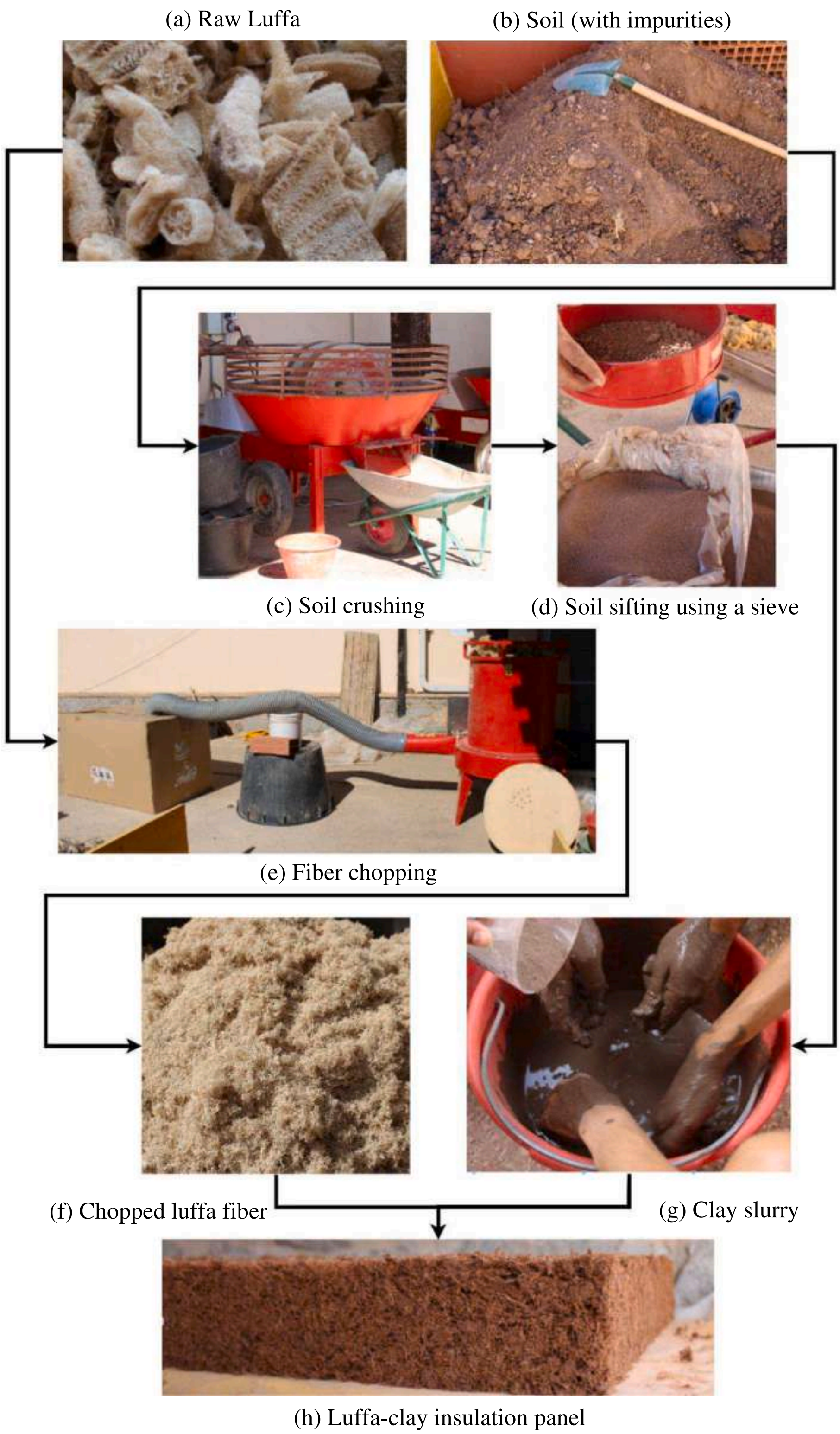


Fig. 5. Schematic diagram of the LC sample preparation.

during autumn to have lower ambient temperature and these panels were left in a place for natural drying with good air circulation for about a month before TC tests were conducted.

The considerations made previously in terms of product homogeneity and surface leveling are also valid for these latter samples.

2.2. Methods

2.2.1. Thermal conductance measurement

Thermal conductance of each sample was determined using a Heat Flow Meter (HFM) instrument - TAURUS TCA, function according to ISO 8301 [64] and DIN EN 1946-3 [68], (Figs. 7 and 8). The testing insulated chamber of the instrument is equipped with two plates. The lower plate is fix, whereas the upper plate can be moved to fit according to the

Fig. 6. Insulation materials: Loofah fiber and clay used as binding material.

Table 3
Amount of ingredients used for LC panels.

Sample nomenclature	Main insulating materials	Binding material		Sample density	
	Loofah fiber	Clay	Water	Mean [kg/m^3]	Co.V [%]
LC	59 %	32 %	9 %	397.6	9.98
Co.V = Coefficient of variation					

sample height which may vary from 5 to 100 mm, as specified by the manufacturer (EN 1946-2 [69]). The functionality of these plates can be reversed to set as hot or cold plate. The plates temperature may vary from −20/+60 °C for the cold plate and −10/+70 °C for the hot plate, depending on the combination of set sample temperature, set plates temperature difference and sample thickness. Both plates have total surface area of 300 × 300 mm, in which exactly at the center they have an active measuring net area of 100 × 100 mm^2. Therefore, the samples surface areas should be considered in between the range of 100 × 100 mm^2 to 300 × 300 mm^2. The samples smaller than 300 × 300 mm^2 must be placed inside a heat guard to avoid and minimize heat losses at the sample edges and also to have quasi-linear heat flow. Each plate's active zone has one HFM at the center. Both HFM and plates have heat protection mechanism against the lateral heat flux losses. To maintain the plates temperature four Peltier devices have been used. The proper functionality of these Peltier devices was monitored using thermal resistance (PT 1000) of Class DIN A. Whereas the instrument has a mini-chiller to extract the dissipating heat, with the help of liquid coolant.

The heat flow meter instrument calculates [57] the TC [W/(m K)] value according to the equation (1), based on the fluxes measured by the hot and cold plates.

$$\lambda = \dot{Q}\frac{S}{(t_H - t_C)}\left[\frac{W}{mK}\right] \quad (1)$$

where, $\dot{Q}$ (W/m^2) is the heat flux; s (m) is the sample thickness; t_H (°C) and t_C (°C) are the hot plate and cold plate temperatures, respectively.

The instrument has the capacity to measure and provide the correct TC [W/(m K)] value in the range of 0.002 to 1.0 W/(m K).

The TC tests were performed according to UNI EN 12939 [70] and the measurements were conducted at 10 °C, 20 °C and 30 °C, when the panels surface temperature difference has been set at 20 K.

The tests were not carried out on dried samples; the same have been left for at least 2 days in the test laboratory where the conditions are kept to 16 ± 1 °C and 65 ± 5 % relative humidity.

2.2.2. *Airborne sound insulation performances*

The air noise is transmitted from one place to another thanks to the vibration of the air which is able to solicit the dividing walls, both horizontal and vertical. The ability of one of them to oppose the passage

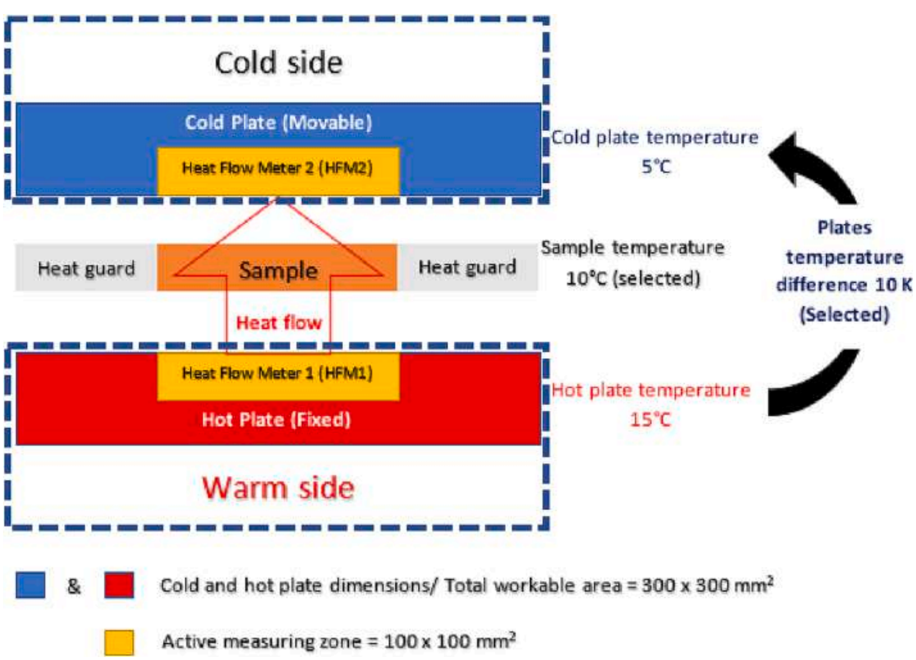


Fig. 7. Schematic diagram of the heat flow meter instrument (TAURUS TAC300).

Fig. 8. Sample JW3 with 250 × 250 mm^2 inside the TAURUS measuring chamber.

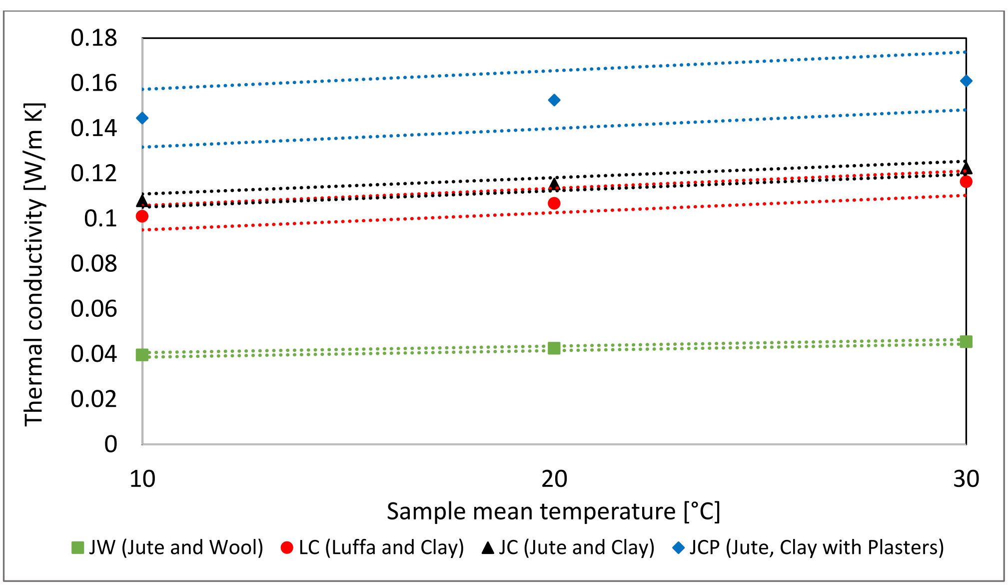


Fig. 9. Thermal conductivity values of different samples test at different sample temperatures and related measurement uncertainty (dotted lines).

of aerial noise, and therefore that of acoustic insulation, is called Airborne sound insulation (R). The latter stands out from the apparent sound reduction index (R') as the first is also said "pure" and refers to the direct component alone, while the second takes into consideration all forms of transmission of sound energy, from the environment issuer to the receiving partner (direct transmission, air lateral transmission and structural side). It is measured in situ by operating the difference between two readings of the foundation made respectively in the environment in which the noise source is placed and the other in the adjacent environment separated from the test element (usually wall or attic). The facade must also isolate from external noises (mainly traffic) ensuring high values of the facade insulation index, which is measured by difference between reading the noise level inside the room and what is externally recorded at the building.

The methodology applied to estimate the airborne sound insulation of the different materials tested in this research is the numerical one described in Annex B (Table B.2) of the international standard ISO 12354-1 [64].

The procedure describes the calculation models to evaluate the insulation from the noise transmitted by air between environments located in buildings, mainly using the measured data that characterize the direct or indirect lateral transmission by the building elements and the theoretical methods on the sound propagation in the structural elements. It describes the principles of the calculation scheme, lists the significant quantities and defines its applications and limitations. In this experimentation concerning the panels with recovered elements, the

Table 4
Thermal conductivity values of the insulation panel made of recycle jute, wool and loofah fiber.

Thermal Conductivity [W/(m K)]				
Sample nomenclature	at 10 °C Mean (Co.V) W/(m K) (%)	at 20 °C Mean (Co.V) W/(m K) (%)	at 30 °C Mean (Co.V) W/(m K) (%)	References W/(m K)
JW (Jute-Wool)	0.040 (1.02 %)	0.043 (0.88 %)	0.045 (0.78 %)	Wool [41]: 0.034–0.040 at 10 °C 0.036–0.044 at 20 °C 0.038–0.048 at 30 °C 0.039–0.050 at 40 °C Jute (100 %) in composite panel [71]: 0.0355–0.049 at 20 °C Jute-polyester (80:20 %) in composite panel [71]: 0.0387–0.0537 at 20 °C
JC (Jute Clay)	0.108 (2.78 %)	0.118 (2.49 %)	0.122 (2.33 %)	Jute in particleboard [57]: 0.067–0,085 at 20 °C
JCP (Jute-Clay with Clay Plaster)	0.145 (8.84 %)	0.153 (8.37 %)	0.161 (8.04 %)	Jute (5 %) with straw-clay [36]: 0.260–0.266 at 20 °C
LC (Loofah-Clay)	0.101 (6.93 %)	0.107 (5.05 %)	0.116 (5.22 %)	Hemp shives (21 %)-clay [56,57]: 0.124 at 10 °C 0.139 at 20 °C 0.151 at 30 °C Sheep wool (4 %)-Lime putty [56,57]: 0.248 at 10 °C 0.257 at 20 °C 0.266 at 30 °C

latter were analyzed from an acoustic point of view through the realization and study of a theoretical model subsequently applicable and available to carry out the practical tests in the laboratory. The airborne sound insulation is calculated through the following formula:

$$R = -10 log\tau\,[dB] \tag{2}$$

where τ (Tau) is the transmission factor, equal to the ratio between the total sound power transmitted in the receiving environment and the sound power incident on the separation element considered. According to [58], τ can be calculated with the following equations:

$$\tau = \left(\frac{2\rho_0 c_0}{2\pi f m'}\right)^2 \frac{\pi f_c \sigma^2}{2f\eta_{tot}} for f \geq fc \tag{3a}$$

$$\tau = \left(\frac{2\rho_0 c_0}{2\pi f m'}\right)^2 \left[2\sigma_f \left(\frac{1-f^2}{f_c^2}\right)^{-2} + \frac{\pi f_c \sigma^2}{2f\eta_{tot}}\right] \text{for} f < fc \tag{3b}$$

depending on the value of the frequency considered, which in turn will be less, greater or about the critical frequency *fc* - reason why it will come measured eighth per eighth. Critical frequency is given by the formula:

$$f_c = \frac{{c_0}^2}{1.8 \bullet c_L \bullet t}[\text{Hz}] \tag{4}$$

where, c_0 is the speed of sound in the air [340 m/s]; c_L is the speed of the almost-longitudinal sound [m/s]; t is the thickness of the structure considered [m].

The sound insulation index (R_w) of each recycled materials were calculated using the procedure as described in ISO 717-part 1 [73].

3. Results and discussion

3.1. Thermal conductivity

In this paper, the authors use waste products suitably mechanically and manually treated, in order to create test samples which will inevitably be characterized by low standardization in terms of size and homogeneous distribution of the components and by possible surface irregularities.

However, it should be noted that all the samples were made following scrupulously processing and drying procedures based on the previous experience of the authors in other similar research activities [16,33,34] and on specific indications found in the literature [36,57].

Although these procedures cannot guarantee adequate repeatability in the homogenization of the various components, they are nevertheless considered adequate in terms of characteristics of the final product (moisture content, percentages by weight of the various components) necessary to allow valid scientific comparison with other samples available in the literature.

The TC values of a total of four samples of each type were evaluated with TAURUS TCA (the heat flow meter instrument) and the results are shown in Fig. 9 (single measurement points) together with the related measurement uncertainty (dotted lines).

The Table 4 presents a comparison between the TC values (measured at 10 °C, 20 °C and 30 °C) of the tested samples JW (as in Fig. 2), JC & JCP (as in Fig. 4) and LC (as in Fig. 6) and TC values of some of the alike materials (available in the scientific literatures). For the purpose of greater clarity, the TC values measured at 20 °C are plotted in Fig. 10, differentiating the cases in which Jute is used with polyester for the construction of insulating panels or mixed in the binder matrix (clay) to increase its thermal performance.

The average values of the recycled JW samples (average density of 20.14 kg/m^3) show TC values variable from 0.040 (at 10 °C) to 0.045 (at 30 °C) W/(m K) with a standard deviation not minor than 0.002 W/(m K). These results are due to the final fibers dimensions and the chosen mixing ratio which allowed to obtain very light panels with a density close to 20 kg/m^3. It is therefore not surprising that even the thermal conductivity values are in line with panels made with wool and similar percentages of polyester, indicating a similar fibrous structure for the different samples [39].

As regards the use of clay, it is possible to note how it always leads to a worsening of the thermal insulation properties, induced by the greater density of the final product. The results generally tend to be dispersive, and it is often difficult to find compatible measurements in the literature. The values in El Azhary et al. [36], for example, are influenced both by a different fibrous structure (straw) and by too modest mixing ratio percentages (5 %) compared to the samples tested in the present work. However, they find correspondence with the results [57] obtained by regarding thermo-insulating retrofitting plasters with a similar mixing ratio (4 %) of natural fibers (sheep wool and thistle), which would suggest a correlation between the two aspects. Instead, by using 22.4 % recycled jute fibers with respect to the binder (i.e. clay) mass, the TC values (average) obtained for JC samples are 15 % lower than values attended for panels made with hemp shives and clay with similar (21 %) mixing ratio [56,57].

The use of materials in polypropylene for jute-polyester-polypropylene sandwich composite panels, in percentages higher than 20 %, seems to guarantee greater stiffness of the panel but tends to decrease its thermal resistance, presumably causing preferential paths for the thermal flow, up to even 20 %. With the same percentage composition of fibrous material, the use of clay as binder material allows for the creation of higher density products (above 800 kg/m^3) but inevitably reduces the porosity of the material and, consequently, the

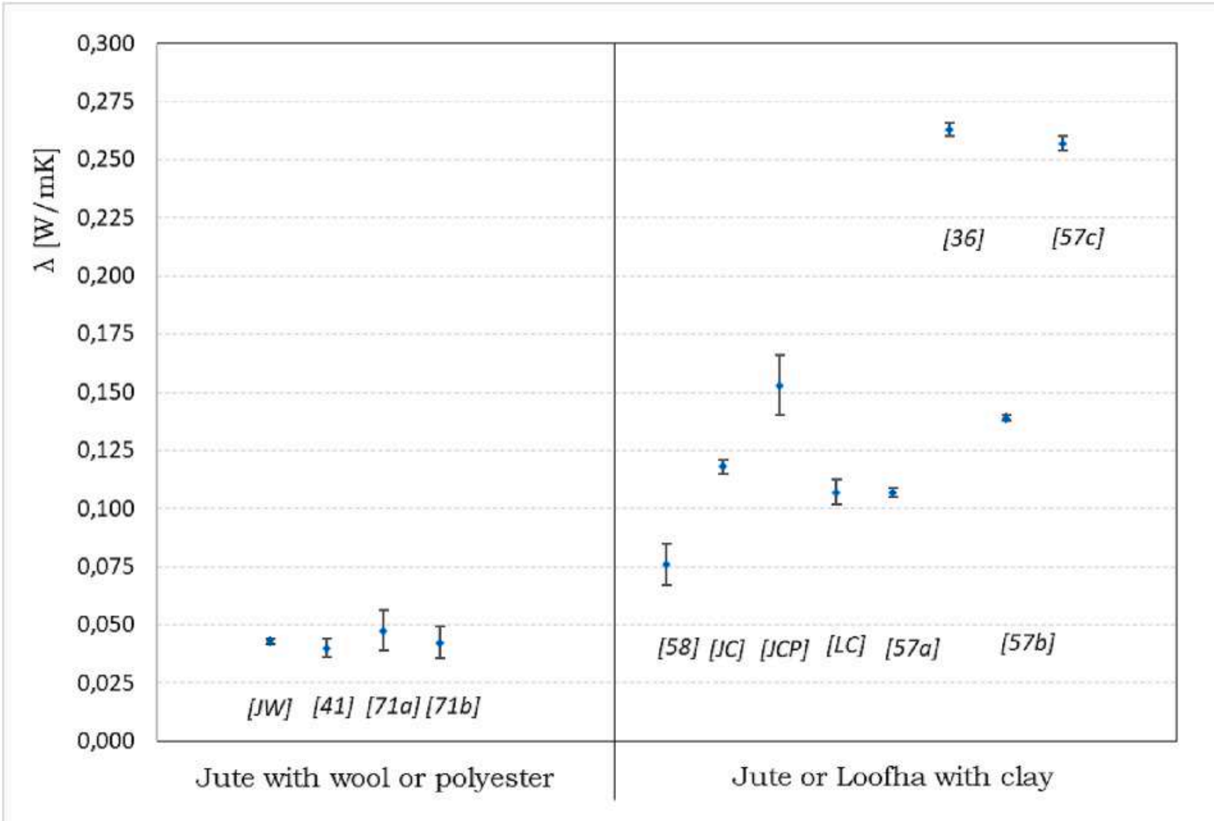
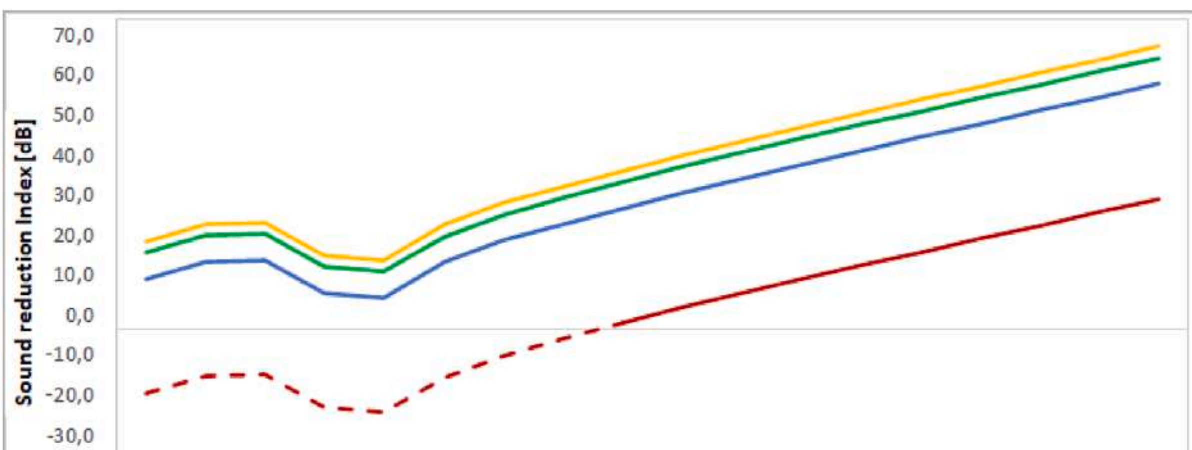


Fig. 10. Thermal conductivity values (at 20 °C) when Jute or Loofha is used in different insulating panels or mixed in the binder matrix (clay) to increase its thermal performance.



	100	125	160	200	250	315	400	500	630	800	1.000	1.250	1.600	2.000	2.500	3.150	4.000	5.000
LC	11,3	15,1	15,5	8,0	7,0	14,9	19,8	23,6	27,2	30,7	33,9	36,9	40,2	43,2	46,2	49,2	52,3	55,2
JC	17,3	21,0	21,4	13,9	12,9	20,9	25,8	29,6	33,2	36,6	39,8	42,8	46,2	49,1	52,1	55,1	58,2	61,1
JCP	19,8	23,5	23,9	16,5	15,4	23,4	28,3	32,1	35,7	39,2	42,3	45,4	48,7	51,7	54,6	57,7	60,8	63,7
JW	-14,6	-10,9	-10,5	-17,9	-19,0	-11,0	-6,1	-2,3	1,3	4,8	7,9	11,0	14,3	17,3	20,2	23,3	26,4	29,3

Frequency band [Hz]

Fig. 11. Airborne sound insulation R of the insulation panels made of recycle jute, wool and loofah fiber.

volume of air trapped. This leads to an increase in the conductivity of the material from 80 % to 250 % depending on the amount of binder used [71]. For example, with the increase in binder (clay) percentage in the mixture (+3 %) and application of 2 mm of plaster, the density of the JCP sample increased (in average) by 34.0 %, have influenced to have 0.015 W/(m K) higher TC values if compared to samples with hemp shives (30 % w.r.t. clay mass) and clay as in [56,57].

Whereas both JC and JCP have shown better performances with respect to the values as highlighted in El Azhary et al. [36], of course this is due to the presence of higher percentage of fibres used.

Table 5
Input data for acoustic simulations.

Input data		unit	LC	JC	JPC	JW
Volume mass of the air	ρ_0	kg/m^3	1,23	1,23	1,23	1,23
Sound speed in the air	c_0	m/s	340,00	340,00	340,00	340,00
Surface mass	m'	kg/m^2	39,76	78,68	105,44	2,01
Transmission factor (sound power ratio)	τ	[-]	0,10	0,10	0,10	0,10
Sound speed in the air	c_L	m/s	2803,80	2803,80	2803,80	2803,80
Critical frequency	f_c	Hz	229,05	229,05	229,05	229,05
Internal loss factor	η_{int}	[-]	0,01	0,01	0,01	0,01

Among all composite samples tested, the best and the lowest TC average values (Fig. 6) at all temperatures were obtained for loofah-clay (LC) sample.

The values obtained for these materials confirms that the addition of fibers to the mortar mixes produces an increase in porosity and a reduction of density, with a consequent reduction of the thermal conductivity [74]. The results highlight a possible twofold choice for the designer:

a) to use insulating panels made with fibrous materials to be positioned on the standard masonry structures: this could be the only possible solution in the case of energy requalification of the existing building;
b) the use of high-performance blocks, using recycled fibrous materials, to replace the standard masonry structures: in this case it would be exploited the greater thermal resistance induced by the porous structure caused by the incorporated fibres.

Both solutions are extremely qualifying in terms of sustainability, being based on the use of recycled fibres. However, bearing in mind the regulatory requirements in force in the energy field [72], on the basis of the results obtained it is possible to estimate in the second solution, with the same final transmittance of the building component, a 25–30 % decrease in the thickness of the masonry component, increasing with the transmittance of the original standard component. It's clear that these observations need to be deepened in broader research that also takes into account the dynamic transmittance, the mechanical properties and the water absorption capacity of the samples made.

3.2. Airborne sound insulation

In Fig. 11 the trend of airborne sound insulation, calculated in frequency bands, in the frequency range 1/3 octave 100 [Hz] to 3150 [Hz] with equation number (2) for the insulation panels under test is shown. The input data for acoustic simulation are shown in Table 5.

The role of their surface mass in eq. 3a and 3b [64] is evident, even with panels with a light structure such as those prepared specifically for

Table 6
Sound insulation index (R_w) value of the insulation panel made of recycle jute, wool and loofah fiber.

Sample nomenclature	Weighted sound reduction index	
	Mean	Co.V
	[dB]	%
JW (Jute-Wool)	00.00	0.02 %
JC (Jute Clay)	31.00	0.89 %
JCP (Jute-Clay with Clay Plaster)	33.00	0.26 %
LC (Loofah-Clay)	25.00	1.02 %
Co.V = Coefficient of variation		

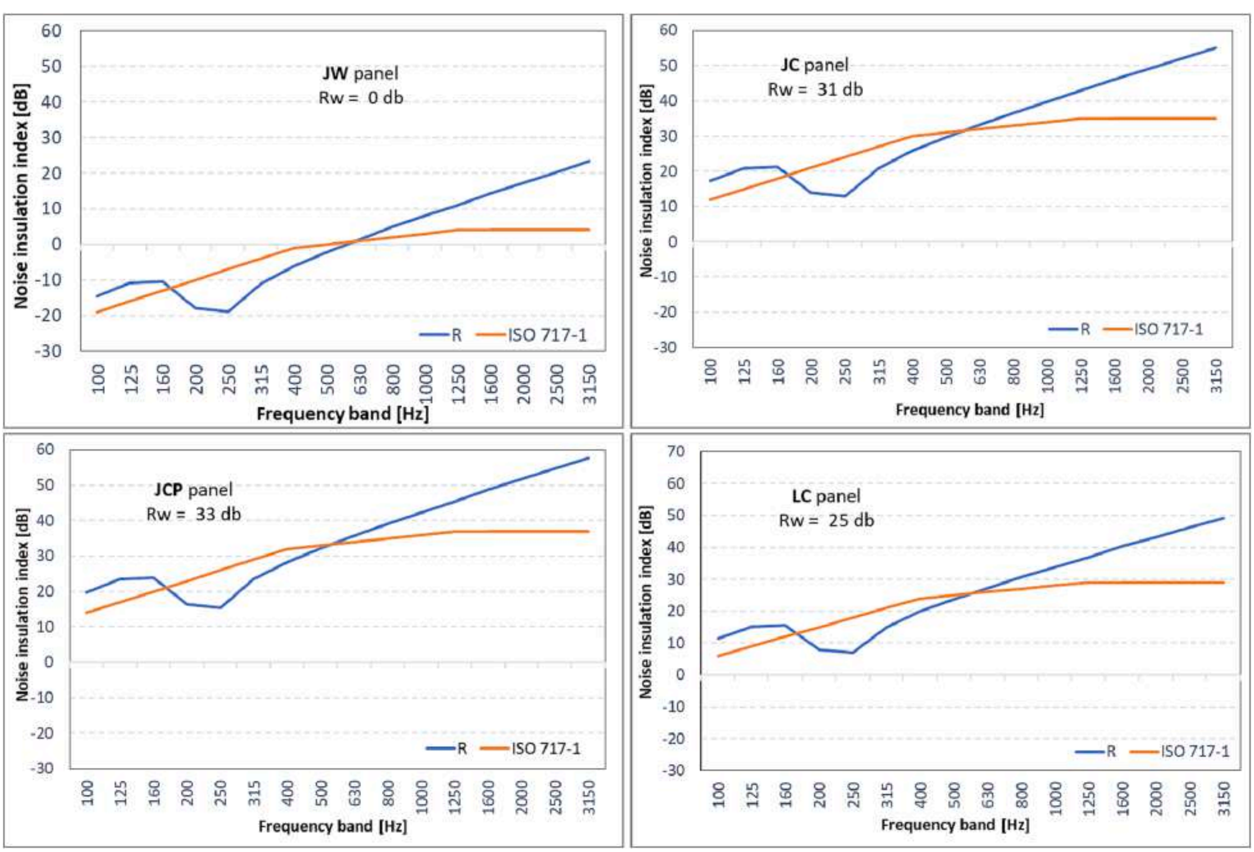


Fig. 12. Sound insulation index calculation (R_w) from ISO 713 for JW, JC, JCP and LC materials.

the present research. In fact, the panels with higher surface mass JPC and JC have the greatest insulation capacity at all frequency bands. The same equations seem no longer applicable for very light structures such as the JW panel, made with sheep wool and having a surface mass just over 2 kg/m^2, for which, below 500 Hz, the sound reduction index becomes negative. This clearly suggests a limited range of validity below. However, this does not affect the purpose of the research which was to have a relative indication of the ability of the different panels to improve the soundproofing power of a generic wall. This aspect will be explored experimentally in a future work by the authors.

The results are reported in Fig. 12 for JW, JC, JCP and LC, respectively, while Table 6 represents the sound insulation index (R_w) values at 500 Hz, as required in [73], for the different recycled panels made with recycle jute, wool and loofah fiber.

The graphs confirm that the contribution of the single layers to the acoustic insulation is variable and strictly connected to the superficial mass of the layer. As highlighted in the introduction, this aspect will be evaluated for the entire wall system with which the single layer will be laid in place. Therefore, the values reported must be considered as a qualitative and non-quantitative indication of the contribution to the acoustic insulation that the individual materials will be able to give in the wall system.

As stated above, the procedure followed for calculating the airborne sound insulation is the some reported in ISO 12354-1 Annex B. Obviously, the measurement errors are those reported in the aforementioned technical standard as it has been applied without making any changes to the calculation procedure described.

It is the intention of the authors in the near future to carry out the study of the acoustic properties of these materials on an experimental basis. Creating experimental walls set up for the structural part in Cross Laminate Timber (CLT) on which to add the materials described in this article as additional layers and performing experimental tests in the laboratory through the procedures described in the ISO 10140 technical standards.

4. Conclusion

During this experimental research work, applicability of newer innovative building insulation materials has been studied. These materials have been fabricated particularly from natural recycled fibers. Predominantly plastic insulation materials are used in construction and building sector for thermal insulation purpose. Therefore, the use of plastic insulation materials in C&B sector can be reduced significantly with the encouragement to use the sustainable insulation building materials (like, jute, wool, loofah etc.).

In this process recycled jute-wool fiber insulation panels were fabricated using the jute fibers collected from the end-life coffee bean carrying jute bags wools collected from the end-life old mattresses. Whereas two types of composite insulation building blocks were prepared with residual raw jute fiber and clay. The raw jute fibers are the residual/waste, have been collected during the masonry retrofitting process. While a layer of clay plaster has been applied on one sample type. The residual/waste loofah fibers come from the loofah fiber products industrial production line and the loofah-clay composite insulation panels have been produced. The thermal insulation properties at 10 °C, 20 °C and 30 °C have been measured and promising results have been obtained for these recycled fibers insulation materials.

As regard the thermal properties it is possible to conclude that they strongly depend on the final fibers dimensions and their mixing ratio with binder. The combinations of jute (40 %), recycled wool (40 %) and polyester (20 %) allowed to obtain very light panels con very porous structure and such as to guarantee thermal conductivity values in line with industrial panels made with sheep wool and similar percentages of polyester. The data doesn't get much worse using it for samples with recycled loofah (60 %) and clay (40 %) indicating a similar fibrous structure for the different samples. As regards the use of clay, it is possible to note how it always leads to a worsening of the thermal insulation properties, induced by the greater density of the final product. The results generally tend to be dispersive, and it is often difficult to find compatible measurements in the literature.

As regard the acoustic properties the sound insulation of the materials carried out with theoretical model provided in ISO 12354 part 1 has shown for the single layer the good property to break down the noise. Exceptions are structures having a very small surface mass for which it seems that the model is no longer valid. In any case, this aspect will have to be overall evaluated to determinate the performance of the building components where the layer of material will be inserted. This is because from the acoustic point of view it is not possible to add the contribution of the single layers to obtain the performance of the system as for the thermal aspects.

The procedures followed in samples' preparation, while cannot guarantee adequate repeatability in the homogenization of the various components, they are nevertheless considered adequate in terms of characteristics of the final product (moisture content, percentages by weight of the various components) necessary to allow valid scientific comparison with other samples available in the literature. It's clear that these observations need to be deepened in broader research that also takes into account their dynamic transmittance, their mechanical properties and their water absorption capacity.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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