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Contribution to thermal and acoustic characterization of corn cob for bio-based building insulation applications

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Abstract

The introduction of the sustainability principle in building design is driving more and more research towards the development of thermal and acoustic building insulating materials using natural- or recycled-based materials and reducing as small as possible energy consumptions during the processes. In this context, among the mostly investigated materials, the corn cob plays an important role although its applications for insulation purposes are still not fully developed. Moreover, the corn cob is often investigated as an aggregate of composite materials, therefore its own thermal characteristics are scarcely investigated. The goal of the paper is to provide a comprehensive contribution to the knowledge of this natural material, from a multidisciplinary point of view, by experimentally assessing at both micro and macro scales, specific heat, thermal conductance, thermal conductivity, and sound reduction index. Results show the specific heat can vary from 1.4 to 1.9 J/gK, according to the given temperature and the investigated corn cob layers, while density is around 200 kg/m^3 and the conductivity, according to the investigated configurations, ranges from 0.14 to 0.26 W/mK. This work suggests a strategy to adopt for the evaluation of natural materials for building construction applications.

Keywords: corn cob; specific heat; thermal conductance; acoustic performance; building insulation; bio-based material.

1. Introduction

Notwithstanding the recent efforts to reduce the building energy consumptions and to increase the adoption of natural or recycled based materials, to date, buildings keep on consuming a significant part of world global energy [1,2] and, what is more alarming, their construction materials are realized in large part with materials that are highly resource-consuming from an environmental point of view during the production phase [3]. These aspects are even more emphasized for building insulation, commonly realized using fossil-based materials or raw natural sources processed with high energy consumptions [4,5].

The introduction of sustainability principle in the building design is gaining more and more attention, particularly in the light of recent post-pandemic events, and with the new surge of the European Green Deal that paves the way for research aimed at studying sustainable innovations in the field, such as thermo-acoustic insulating materials using natural-based or recycled-based materials. Indeed, recent review papers in the field [3,6–8] report the thermoacoustic properties of different agriculture products, as bagasse, bamboo, banana stalks, coconut coir, cork, corn stalk and cob, cotton stalks, date palm, durian peel, hemp stalk, kenaf fiber, oil palm leaves, pineapple leaves, rice husks and straw, sunflower hulls and stalks, wheat straw (bale). Some experimental campaigns have considered the raw materials whereas other used derived products such as granulated material, particleboard, hardboard, fiber board. On the other hand some studies investigated the thermal behavior of recycled materials obtained with textile waste [9,10], wood waste [4], recycled plastics and glass waste. The adoption of natural or recycled raw materials drives to several direct advantages such as the reduction of the depletion of non-renewable resources, the reduction of the quantity of waste for the disposal, the reduction of energy needs to produce the materials. Moreover, the usage of agricultural by-products and waste can provide further benefit since on one side they can be recycled in the proximity of the production area, reducing environmental costs impacts due to transportation and manufacturing and, on the other side, their usage as building material can be considered an avoided emission of CO_2 or, properly, a carbon stock.

Despite the considerable research efforts for the experimental assessment of the thermoacoustic properties of these unconventional materials, the full exploitation of their potential is still far. In fact, only few of them, such as cork, hemp, kenaf or wood fiber, are already on the market but, bypassing the wide skepticism with solid performance data, their diffusion could be further improved since their performance is indeed similar to synthetic materials [11]. Some current difficulties for their commercialization are the characterization and the standardization of the performances obtained from the products based on natural materials [12] and the difficulty to ensure a proper durability for natural materials.

Among the vegetable products cited above, corn cob is one of the most investigated raw material for building insulation applications and the physical properties characterization and thermo-acoustic assessment are the most important parameters to be evaluated [13,14] for practical applications. Indeed, application of such alternative products in the building sector, in particular as insulation materials, needs still several tests to validate their suitability as construction material and also in meeting law requirements.

To this point, the main goal of the paper is to provide a contribution to the knowledge of this natural material, usually considered a maize production waste, by experimentally investigating and evaluating some of its thermo-acoustic properties. A novelty contribution of the paper are the values of the specific heat experimentally obtained for different layers of the cob for different temperatures. A second aspect concerns the experimental assessment of the conductance of wall samples realized with corn cobs oriented in different ways. Finally, the relation between microstructure of corn cob and thermal properties is analyzed.

Also recently, corn cobs have captured the attention of some researchers as a potential byproduct especially as abrasive material, or for the production of lightweight concrete for nonstructural applications and building insulation [15]

In Pinto et al. [16] the authors investigated the macrostructure and microstructure, elementary chemical composition, density, water absorption and fire resistance of the corn cob. The cob properties were compared with those of commercial products in the field of thermal insulation. Some similarities were found between the analysed products so suggesting that the corn cob could be used as raw material in thermal insulating products. The main properties of raw corn cobs and corn cob particleboards have been experimentally evaluated in [17] showing performances similar to the synthetic materials and providing the viability o become a potential source for bio-based insulating materials. In [15] the authors observed that corn cob presents three layers different in shape, texture, density and color. The cob materials are heterogeneous, in contrast to common thermal insulation building materials, which is related to their origin being a natural biological material. In [18] the production and development of panels realized with a composite corn cob have favourable physical properties recommendable for indoor uses in buildings. In contrast, the particleboards cannot be used for load bearing purposes based on poor mechanical properties of the material.

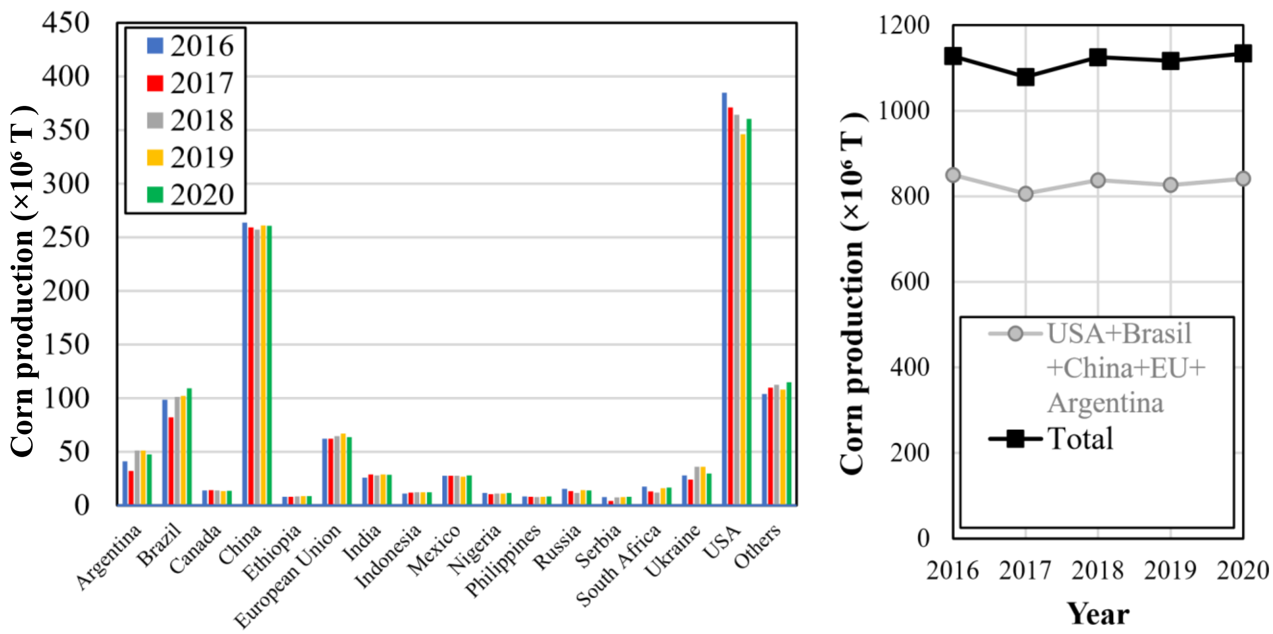
Despite the wide academic interest, corn cob applications for insulation purposes is still not ready for the market, requiring to fill some knowledge and technological gaps. To this point, the objective of the paper is to provide a further contribution to the knowledge of this natural material, usually considered a maize production waste, by experimentally investigating and evaluating some of its thermo-acoustic properties.

In fact, in the present paper, the microstructure of corn cob has been investigated by means of scanning electron microscope and spectroscopic investigations. Then, the specific heat value for different layers of the cob, currently not available in literature for different temperatures, has been evaluated by means of differential scanning calorimetry technique applied to specific specimens sampled in different corn cob layers. This represents a first attempt to assess this important parameter for corn cob, in the range 0°C – 40°C. Finally, the thermal performance of the cobs has been assessed from a macro-scale point of view, by testing six different wall samples filled with cobs laid in different configurations. For each configuration, the wall conductance value has been evaluated by means of a movable hot box to identify important thermal characteristics of the investigated material [19] and not only as a component of composite material [20].

2. Corn plant features: diffusion, production and actual end-of-life

In the corn production process, the main product are the grains whereas all the rest of the plant is generally considered as a waste component [21] and most of the corn stover (i.e. stalk, leaves, husks and cobs) is commonly left in the field after grain harvesting since believed not useful for other purposes. The most investigated portion of the corn stover is the cob, seeing as how its particular features make it valuable in the building sector for applications as insulation material or in the mix-design of cement-based materials. In addition, a wealth of studies confirms that the cobs left in the field does not bring any important benefits to the culture. In fact, as residue in the field, the cobs could play a role in soil and water conservation and in soil nutrient dynamics since they provide surface cover and contains carbon and nutrients. However, on one hand in [22], erosion, runoff and nutrient loss by rainfalls were proved to occur irrespective of cobs removal, and on the other hand, in [23] carbon and nutrient dynamics monitoring during the year after harvest showed a decline in cob carbon content in field proving that only small nutrient concentrations are made available for the crops during the first year of cob decomposition. Hence, cob harvesting provides low nutrient removal. Moreover, the cobs could be potentially collected during the grain harvesting operations since several combines able to collect cobs have been developed and tested [24–26]. Thus, corn cob can be considered an abundant and inexpensive biomass that can be removed from the field without deleterious effects. Figure 1a shows the yearly geographical distribution of maize production for some recent years and as reported in Figure 1b the total world maize production results rather stable in the years 2016-20 around 1.1×10^9 T/year [27].

As far as the potential available cob quantity is concerned, in [28] the authors have estimated that in field residual after grain harvesting is about 8.9 t/ha that could generate, at European level, about 85 Mt/year of corn stover. If we consider that corn cobs represent about 20% by weight of the stover we should estimate a yearly cob yield of about 15 million tons, only at European level.



(a) (b)

Figure 1. Trend of corn (grains) production in recent years. (a) Yearly production of countries/regions with the highest yield. (b) World production and sum of the productions of the five countries/regions with the highest yield.

3. Experimental micro-scale tests on corn cobs

This paper reports the main results of the experimental tests performed on a large quantity of corn cobs collected during the maize harvesting of the September 2019, in a farm located in the North of Italy. The cultivated maize class has been the PR32B10 (Pioneer seed), i.e., one of the most productive white maize species for grains in temperate climatic conditions (when facing with natural materials, it is extremely important to declare the crop class since properties and results of the investigation could be considerably affected from the considered species). For the experimental tests, about 200 kg of corn cobs have been randomly collected in field during the threshing and then dried in drying-heating chamber with natural convection (Binder, ED 720) keeping the cobs for 72 hours at 120°C. In a first phase, prior to the laboratory tests, five random samples, each one composed of 10 cobs (see Figure 2), have been realized by selecting the cobs from different plots of land of the farm, to avoid biases in the laboratory test outcomes. Then, length, maximum diameter, and weight of the 50 cobs have been measured and the average and the coefficient of variation (CoV) values calculated. Table 1 collects the main results of the dimension characterization process.

Table 1. Results of the dimension characterization process.

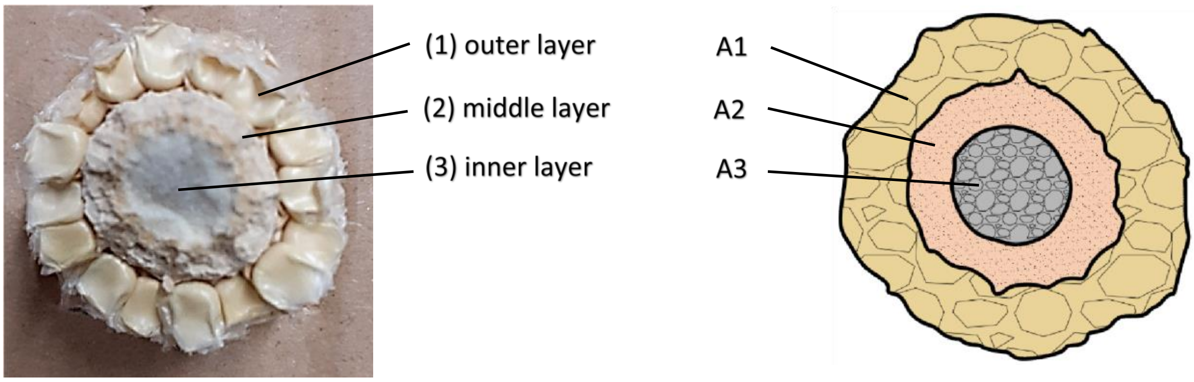
Statistical measure	Length	Diameter	Weight dry
Average value	192 mm	28 mm	34.7 g
CoV	11.6 %	5.9 %	26.5 %

The values in Table 1 show that, despite the natural origin, cob dimensions are characterized by little dispersion and comparable with other natural materials (e.g., timber). In the perspective to adopt corn cobs as alternative building material, their principal properties must be determined. The following sub-sections report the main outcomes of the micro-scale tests performed on corn cobs and aiming to increase the current level of knowledge of this material. The tests described in this Section followed procedures prescribed by international standards or validated in previous works and the tests were performed by using certified equipment. In order to confirm the reliability of the results, the main outcomes of the tests were then compared with those available in literature.

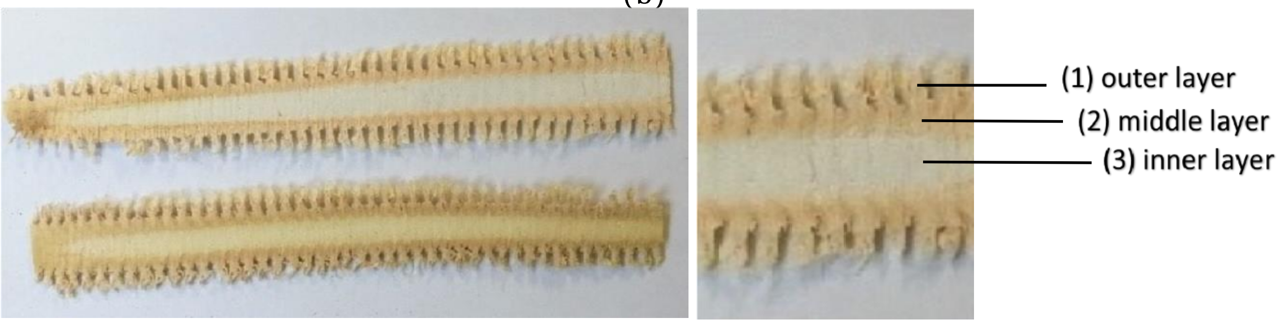
3.1 Microstructure of a corn cob

The concentric macro-structure of a cob has three different layers that can be distinguished from each other even with the naked eye on the basis of colour and consistency (see Figure 2). The outer layer (i.e. layer 1 in Figure 2), which supports the caryopsides, is characterized by a crown with many voids alternating with thin leaflets. The darker middle layer (layer 2), with low presence of cavities, much harder and with wood-like texture; an inner layer (layer 3) with many polygonal cavities characterized by a soft and easily compressible consistency. The cob structure is similar to that already observed in [15] and this confirms, the general result that, although the different authors have investigated various species of corn, widespread in different regions of the world, the main features characterizing this material are common and usually well reproducible.

(a)



(b)



(c)

Figure 2. Definition of the macro-structure of corn cob. (a) Sample of some dried cobs collected for the experimental tests. (b) Transverse section and (c) longitudinal section of a corn cob.

Micrographs of the cob micro-structure were taken in different corn cob portions of different corn cobs collected for the experimental campaign, with a Scanning Electron Microscope (SEM) ZEISS EVO 50 EP in Environmental mode with a pressure of 100 Pa in the chamber. As described before, the images of the various layers of corn cob highlight a significant difference in their morphology and SEM micrographs taken on the same cob could display a different arrangement. The inner core of the cob (layer 3) shows (Figure 3A) an airy morphology with thin layers of filmy material arranged to form cavities and porous structures. The middle portion, i.e. layer 2, instead, clearly displays (Figure 3B) a denser and more compact aspect, with almost no cavities. There is no more a thin film morphology for the lignocellulosic components, that appear bulky and thick. The outer portion, i.e., layer 1, is the most complex from the morphologic point of view, since it shows both a filmy and compact aspect (e.g. Figure 3C), that sometimes displays holes and cavities (see Figure 3D) that however are not as porous and airy as the morphology observed in the inner core samples.

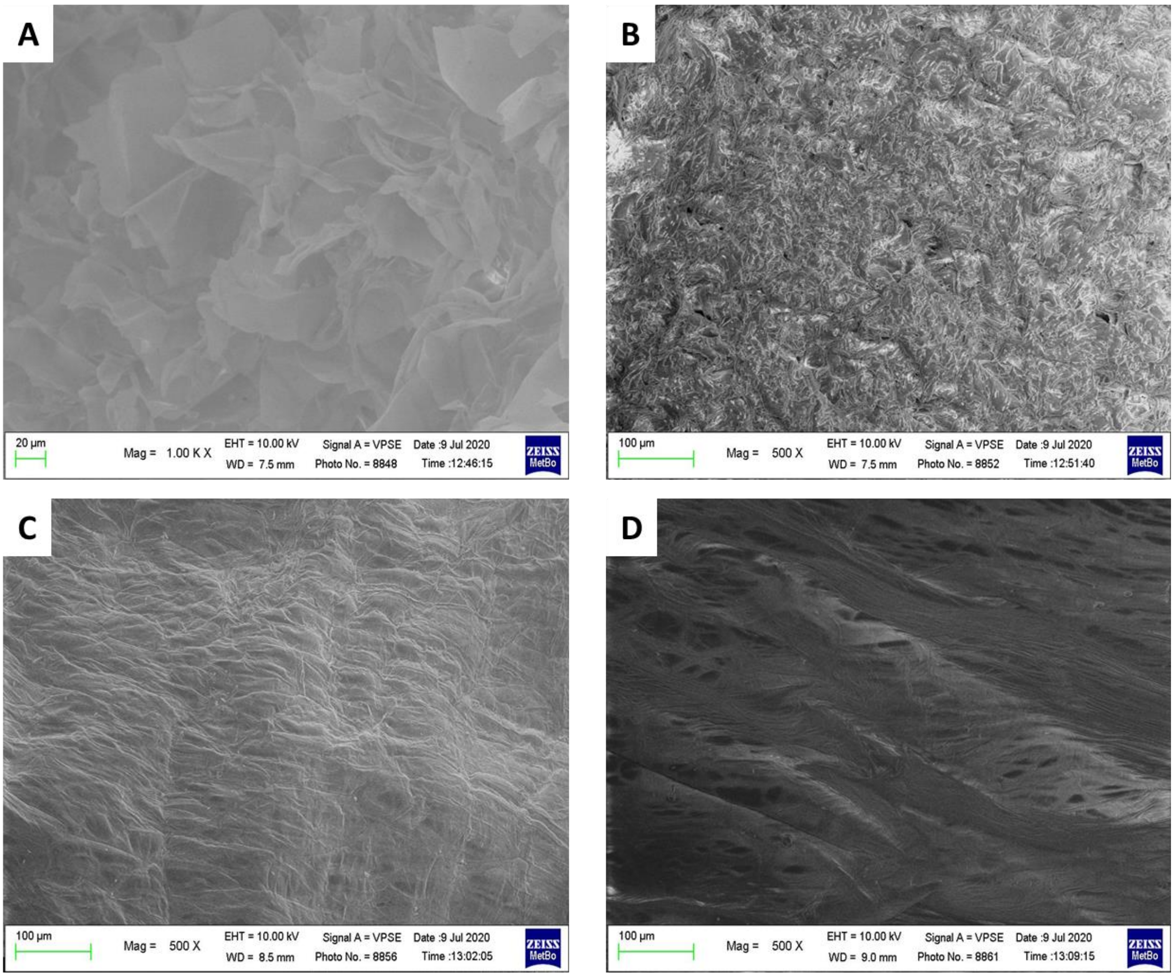


Figure 3. SEM images of the micro-structure of a corn cob: (A) inner layer (1000X), (B) middle layer (500X), (C) and (D) outer layer (500X).

The different morphologies of the cob confer to the whole material very particular properties, and as discussed in the following sections, the inner layer is maybe the most interesting to study and characterize from a thermal point of view, in view of the potential application in building insulation.

3.2 Density and water absorption

The material density (□) has been investigated in laboratory on a representative sample of 30 cobs. Corn cobs – as well as many natural-based materials - show density variations related to the water content (*W*) and thus, it is difficult to define a single density value since it strongly depends on the moisture of the investigated sample. In fact, it can be assumed that corn cobs density is a function of the water content of the investigated sample. Thus, the material density has been calculated for different water absorption values in order to evaluate the expected trend for the material for some points of interest. To this regard, the water absorption capacity of the cobs has been calculated following the EN ISO 16535:2019 [29] which represents the standard for the calculation of long-term water absorption, by immersion, of products for thermal insulation of buildings. In the present study the method 2A of EN ISO 16535:2019, considering the total immersion of the samples, has been considered. As a matter fact, the water absorption by total immersion is not directly related to conditions on site but has been recognized as a relevant testing condition for some applications. Four different characteristic points have been considered:

Point 0: dried (d) condition of the samples

Point 1: samples immerged in water for 10s providing an instantaneous (i) condition

Point 2: sample immerged in water for 72 hours providing a short term (st) condition

Point 3 sample immerged in water for 28 days providing a long term (lt) condition

At first, the cob dried mass was measured (M_d). Afterwards, 10 sub-samples, each one with 3 corn cobs, were immersed in a control volume ($V_{control}$) of distilled water at a temperature of 20°C. The final volume (V_{final}), after the immersion of cobs and ballast, was measured (see Figure 4). Thus, if $V_{ballast}$ is the known volume of the ballast preventing the buoyancy of cobs, the differential volume (ΔV) resulting from the difference:

$$\Delta V = V_{final} - V_{control} - V_{ballast} \quad (1)$$

was quantified and considered equal to the cobs volume (V_{cob}). Finally, the dried density ρ_d of each sample was quantified as ratio between dried mass M_d and V_{cob}. The mean value of the dried density of the corn cob was 247.23 kg/m^3, with a CoV equal to 4.3%. This latter value is lower than that found in [16], since the CoV value reported here is calculated on average density of 3 cobs constituting one sample. The mean density value is in the (expected) range from 171 kg/m^3 to 334 kg/m^3 provided in [3]. This is an interesting result since it shows that corn cob density value is rather narrowed and, in general, the scattering of the density values is limited and comparable with those of other natural building materials. The density value of the corn cob results from a weighted average over the three different layers of the transverse section, with the densest portion, i.e., the middle layer (2), that plays the main role in the definition of the such value. As will be shown in a following sub-section this affects the thermal properties of the material in a considerable way. Analogously, the density values ρ_i, ρ_{st}, and ρ_{lt} have been determined for the instantaneous, short-term and long-term immersion conditions respectively, by considering the immersion interval periods before cited. The measuring of the different cob mass values has been realized following the indications in EN ISO 16535:2019 so draining for about 10 min the samples before weighing. The obtained average and CoV values are reported in Table 2. The instantaneous measures are those affected by the highest dispersion since, in this case, the water quantity absorbed by the cobs in just 10 s is strongly related to the perimeter roughness of the cob. Instead, the dispersion of the density values after 72h and 28d is practically negligible. It is to noteworthy that after 72h (i.e. 3 days considered for the short term condition) the cobs adsorbed practically the same amount of water as in the long term condition, i.e. after 28 d of immersion. So, after 3 days the cob could be considered saturated by water.

Table 2. Main results of density and water absorption assessment.

Density

	ρ_d	ρ_i	ρ_{st}	ρ_{lt}
Average (kg/m^3)	247	279	793	812
CoV (%)	4.3	8.9	2.2	2.1
Water absorption				
	W_d	W_i	W_{st}	W_{lt}
Average (%)	0	2.96	54.67	56.53

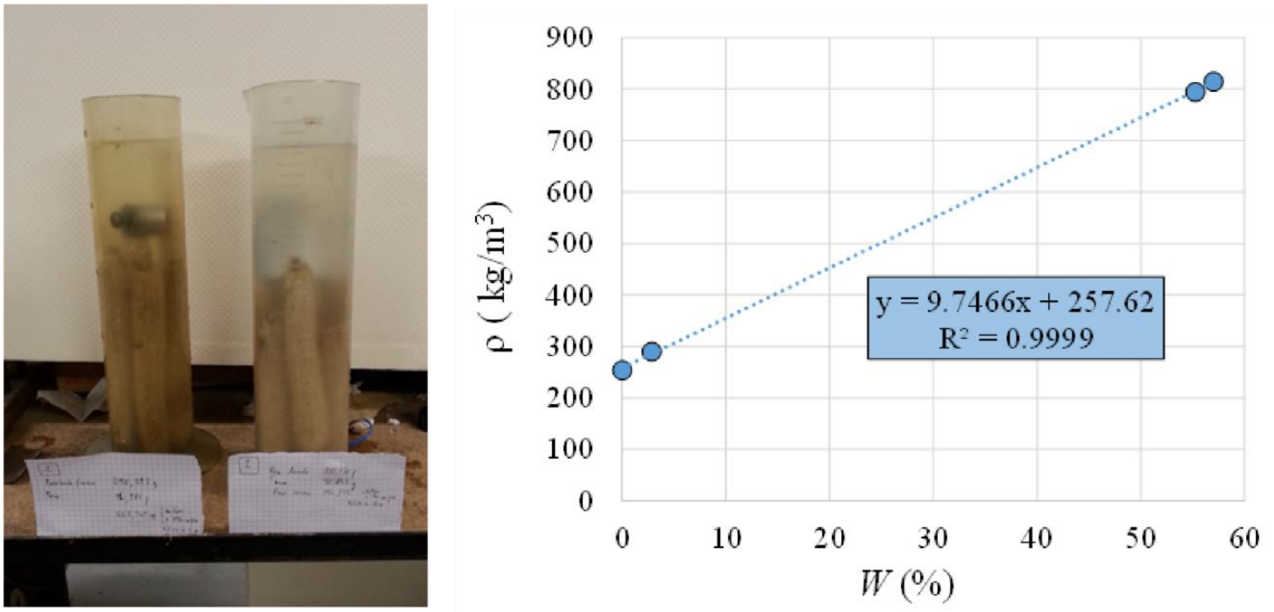
Following the approach of the Method 2A in the EN ISO 16535:2019, the percentage water absorption values have been calculated, for the above cited conditions, according to the following equations:

$$W_i = \frac{m_i - m_0}{V_0} \times \frac{100}{\rho_w} \tag{2a}$$

$$W_{st} = \frac{m_{st} - m_0}{V_0} \times \frac{100}{\rho_w} \tag{2b}$$

$$W_{lt} = \frac{m_{lt} - m_0}{V_0} \times \frac{100}{\rho_w} \tag{2c}$$

where: m_i, m_{st} and m_{lt} are the mass values defined before; m_0 is the initial mass of the test specimen assumed equal to m_d; V_0 is the initial volume of the test specimen assumed equal to V_{cob}; ρ_w is the density of water, assumed to be 1000 kg/m^3. The values calculated for the different conditions are reported in Table 2 where, obviously, the value of W_d is set to 0 because $m_d = m_0$. According to the results reported in Table 2, the corn cobs display a noteworthy water absorption capacity when totally immersed. This confirms the outcomes in [16] but at the same time raises doubts about the need to perform specific durability tests for the material, especially when applied in contexts with high humidity rate. This aspect is out of the scope of the study but will be object of future investigations. It is interesting to plot ρ values Vs. the related W values (see Figure 4b) in order to identify the expected linear relation between the two measures. The fitting equation for the sample investigated in this paper is reported in order to easily move from ρ to W and vice versa.



(a) (b)

Figure 4. Tests for the evaluation of the density of corn cobs. (a) Immersion of the cobs in graduated cylinders for the determination of the material density. (b) Correlation graph between W and ρ.

3.3 Spectroscopic investigation

Different corncob samples have been collected from inner, middle, and outer layers so to separately investigate the different portions of a cob and to evaluate any variation between layers in chemical composition. Fourier Transform Infrared Spectroscopy (FTIR) measurements have been performed with attenuated total reflection (ATR) sampling technique alongside traditional infrared spectroscopy by using an ATR-FTIR Alpha instrument (Bruker, US). The samples have been placed on a crystal (diamond) without any prior preparation. The spectra of the three different layers have been obtained with 32 scans in the spectral range from 4000 cm^{-1} to 400 cm^{-1} with a resolution of 4.0 cm^{-1}. The spectra are reported in Figure 5. A relevant absorption is observed at 3300 cm^{-1}, characteristic of OH stretching of lignin. At 1730 cm^{-1} it is observed the C=O unconjugated stretching of acetyl groups from lignin and hemicellulose. Moreover, another peak is present at 1240 cm^{-1}, deriving from aromatic C-O stretching of xylan (hemicellulose). At 1160 cm^{-1} and 1035 cm^{-1} respectively the C-O stretching in ester groups and C-C, C-OH, C-H ring and side group vibration of hemicellulose, cellulose and lignin are visible. In confirmation of [30], the reported ATR spectra revealed that the main components are hemicellulose, cellulose, and lignin. Anyway, the three spectra are very similar and this leads to assume a similar chemical composition of the different layers of corncob even if with some little differences on the various group percentages.

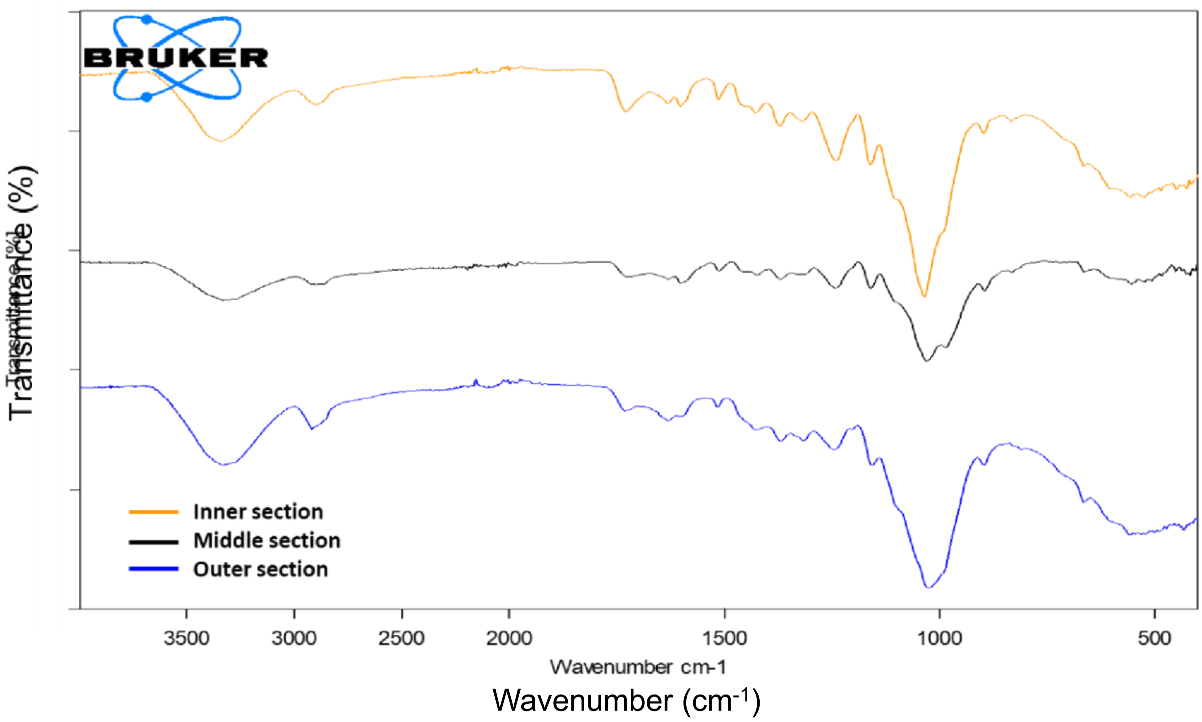


Figure 5. ATR spectra in transmittance of the different corn cob layers.

3.4 Specific heat evaluation

For the thermal characterization of an insulating material, probably the most representative parameters are the specific heat, usually defined as C_p and the thermal conductivity, usually denoted by □ □□□□. To this regard it seems worth to recall that C_p (J/(g·K)) of a substance or material is defined as the amount of energy, in the form of heat, required for one unit of mass of the material in order to cause an increase of one unit in the temperature, whereas □ (W/(m·K)) is a measure of the ability of a substance or material to conduct heat. Both, C_p and □ are function of temperature and typically they are higher at elevated temperatures [31]. On the other side, in the context of thermal insulation of buildings, by using nomenclature in [32,33], the thermal transmittance U ($W/(m^2·K)$) or the thermal conductance □ ($W/(m^2·K)$) of an envelope are among the most important properties to define, according to the intended use of the building [34]. In fact, most of the energetic performances of a building could be directly or indirectly correlated to the performance of the envelope materials.

In the present work C_p has been assumed as reference parameter for the evaluation of the of corn cob thermal property whereas □ of some corn cob configurations (discussed in a following section) has been investigated as possible insulation material in building envelope. Hence all the single cob layers (outer, middle and inner) have been singularly analysed in order to determine any difference in the C_p that might help to build a more thorough thermal model of the behaviour of the corn cob. It is interesting to highlight that, contrarily to other bio-based materials, results on C_p value, for different temperatures, for corn cob as raw material seem to be not available in scientific literature [3].

C_p has been investigated by means of an experimental campaign performed using the differential scanning calorimetry (DSC), i.e., a thermo-analytical technique that relates Cp to the temperature according to the amount of heat required to increase the temperature of a sample is measured as a function of the temperature. The measurements have been carried out with a DSC Q2000 (TA Instruments, US) calorimeter equipped with a refrigerated cooling system (RCS90). The analyses, calibrated for the evaluation of C_p at 20°C as reference temperatures, have been carried out with a 10°C/min heating rate in the temperature range from -10°C to

+50°C with 1 point/second as sampling interval, after setting the zero heat flow point at 20°C prior the beginning of the heating scan. Then values were also extrapolated at 0°C and 40°C for comparative purposes. A cell calibration is required prior to perform C_p measurements. A sapphire standard sample has been employed to perform the calibration. For each cob layer, i.e. outer, middle, and inner, five samples have been extracted from different corn cobs randomly selected and then analysed for the C_P assessment.

In addition, in order to investigate the thermal properties of corn cob powder for a possible application as material for insulation panels, five specimens have been obtained from corn cob ground to powder and then pressed with a pelletizer press applying a pressure of 5 bar for 20 minutes each one. The five pressed powdery pellets have been tested in the DSC Q2000 (TA Instruments, US) calorimeter with the aim to provide for a reference of the performance of the same material but in a different arrangement.

The main results of the calorimetric tests are reported in Figure 6 that presents the trend of C_p as a function of the applied temperature in the 0°C - 40°C range. As the figure shows, the five companion specimens provide limited difference in the trends and a good repeatability. The highest dispersion is exhibited by the inner layer (see Figure 6c) and this finding was expected because of the irregular texture highlighted by the SEM images.

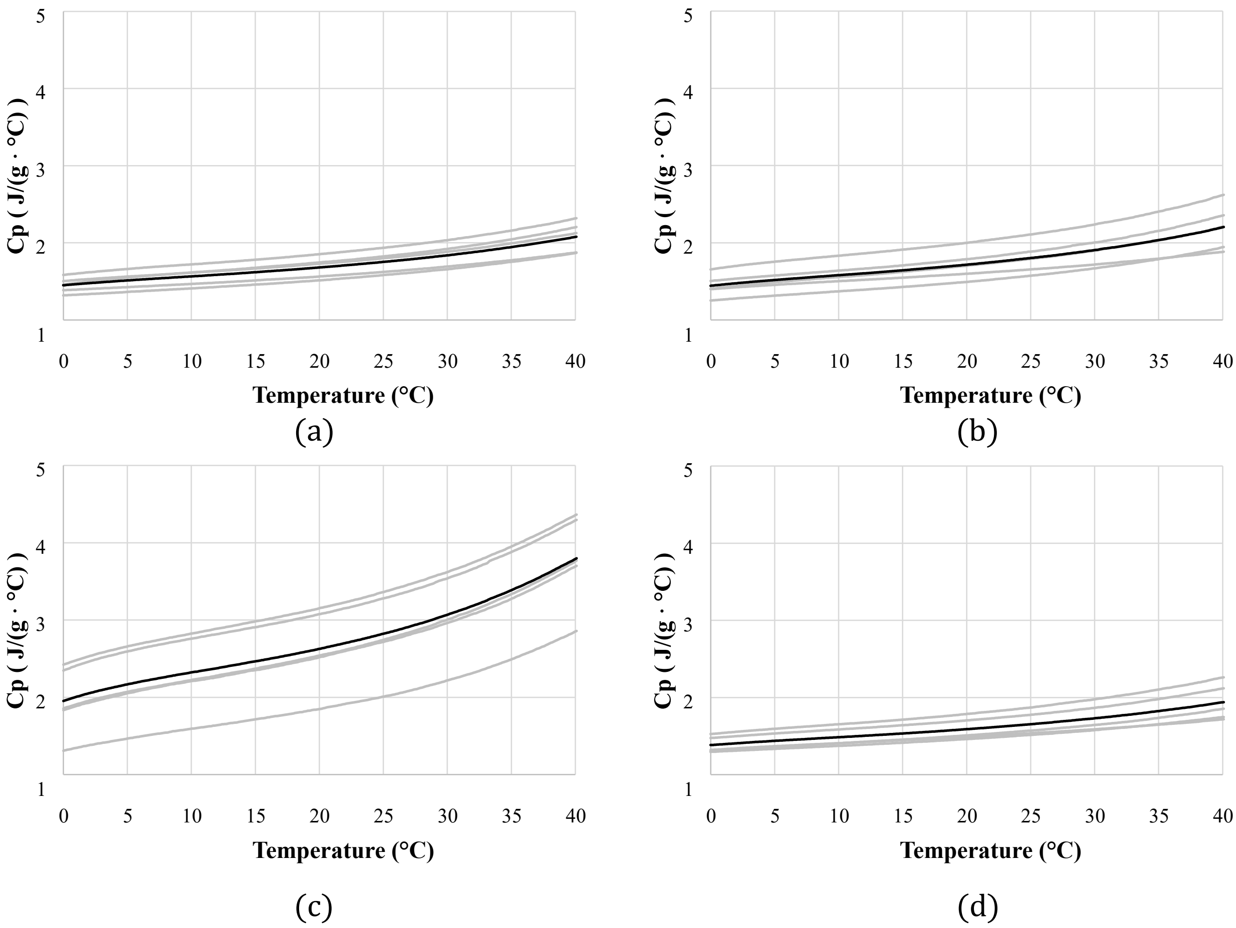
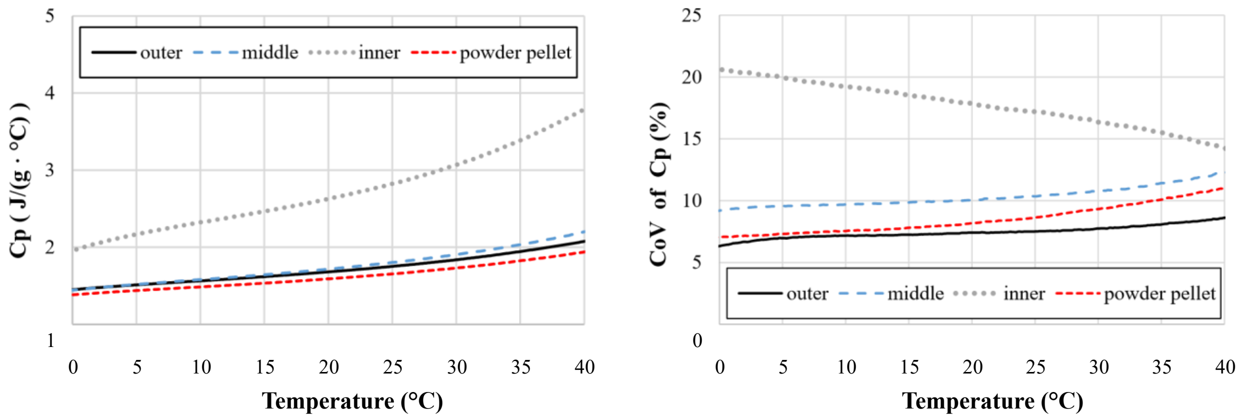


Figure 6. Experimental Cp curves for different corn cob layers and samples (grey line indicates single sample curve; black line indicates the average curve). (a) Outer layer. (b) Middle layer. (c) Inner layer. (d) Powder pellet.

For the sake of a comparison, the average C_p trends of the different sample types and the related CoV values are summarized in Figure 7a and 7b respectively and furthermore, Table 3 collects these values for the three reference temperatures (0°C, 20°C and 40°C). Comparing the different layers of corn cob it clearly appears that inner layer shows the highest C_p values, ranging from 1.9 J/(g·°C) to about 3.8 J/(g·°C) and is about 2.6 J/(g·°C) at 20 °C temperature (the latter being usually assumed as reference for characterization of insulation elements). This value is higher than about 50% with respect to the other layers. In fact, the outer and the middle corn cob layers display C_p values respectively 1.68 J/(g·°C) and 1.72 J/(g·°C) at 20° C. The comparison displays that the inner layer requires more energy to increase its temperature than the other corn cob layers. The difference between the inner and middle/outer layers could be attributed to the different morphology of the corn cob areas, as indeed observed with the SEM micrographs (see Figure 3). In fact, an elevated void content, could affect the main material macroscopic thermal properties, like the specific heat.



(a) (b)

Figure 7. Comparison of the results obtained from the experimental tests on different types of corn cob layers and samples. (a) Average Cp curves. (b) Coefficient of variation curves of the Cp values.

Table 3. Average Cp (J/(g·°C)) and related CoV (% data in the brackets) values for different corn cob sample types and different reference temperatures.

Temperature	Outer layer	Middle layer	Inner layer	Powder pellet
0° C	1.449 (6.3)	1.443 (9.2)	1.954 (20.6)	1.384 (7.1)
20° C	1.680 (7.4)	1.716 (10.0)	2.628 (17.9)	1.590 (8.2)
40 °C	2.076 (8.6)	2.200 (12.3)	3.790 (14.3)	1.938 (11.0)

It could be useful to obtain a single C_p value that take into account all the three different layers of a corn cob. In order to calculate a C_p value, average on the volume (Cp_{vol}), the following formulation for composite materials derived from [35] can be adopted:

$$\overline{Cp} = \frac{1}{V_{tot}} \sum_i Cp_i \cdot V_i \tag{3}$$

where C_{pi} is the C_p value of the i-th component; V_i is the volume of the i-th component in the considered mass; V_{tot} is the total volume of the considered mass. The preliminary analyses, described in the previous sub-section, provided that the volume percentages of the three single layers of a corn cob (which the areas A1, A2 and A3 in Figure 2b refer), on average, are equal to

60%, 26% and 14% for outer, middle and inner layer respectively. By introducing these percentages in Eq.(3), the Cp for a temperature equal to 20°C is 1.82 J/(g·°C). Following the results provided in this paper, the latter value can be assumed as representative value for the whole corn cob.

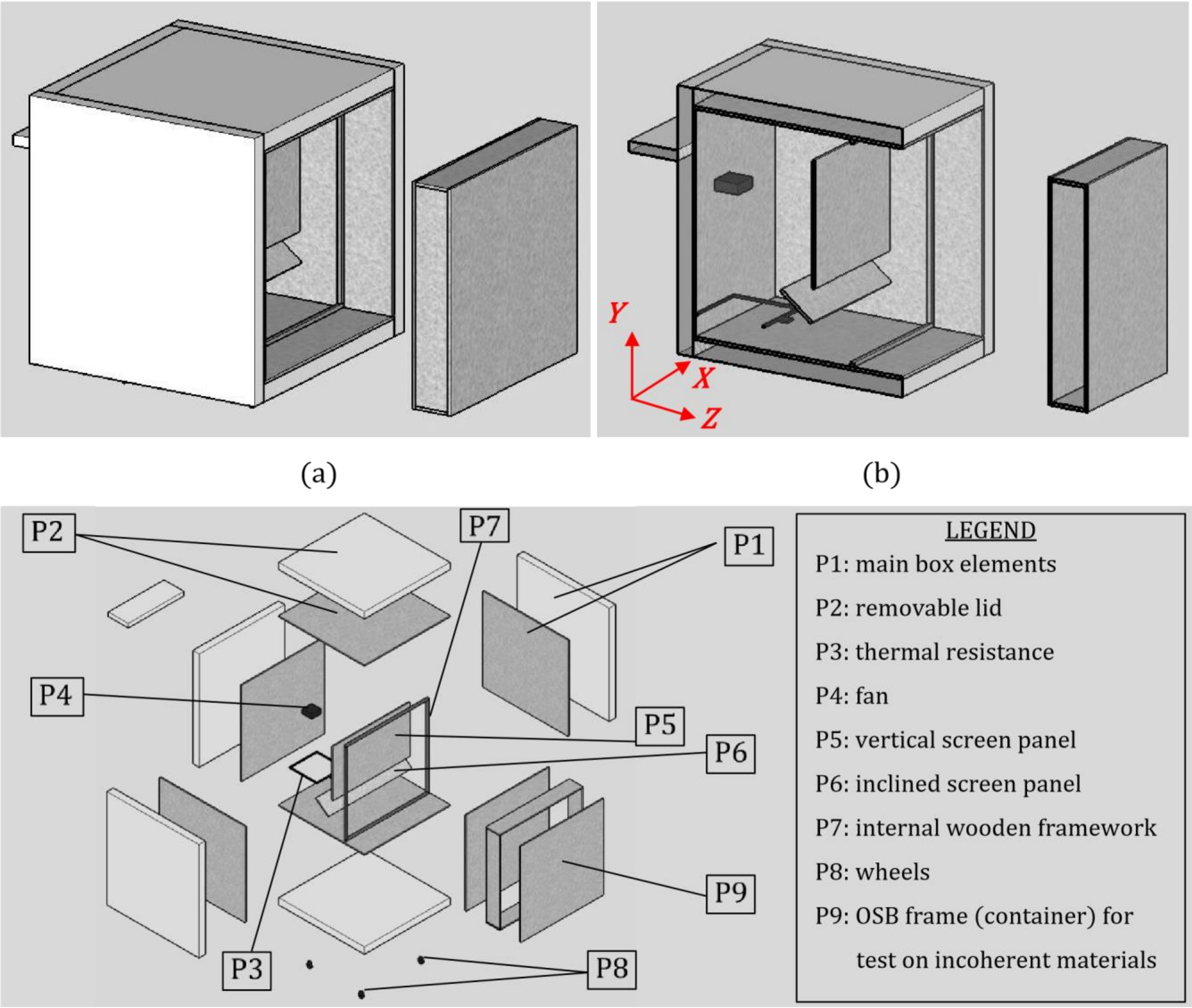
As far as the results of the tests on powder pellet specimens are concerned, the C_p values show a slight decrease all along the investigated temperature range (see Figure 7a), but practically very similar to the trends of middle and outer layers. This is because the process of compressing the corn cob powder probably eliminates most of the voids contained in the inner layer thus making the contribution of the latter negligible in the definition of the final C_p value for the pellets. However, these values confirm that a generic material derived from the corn cob through a compression process of the base raw material does not have a significantly worsening of the thermal properties with respect to the original material.

Finally, the C_p values deduced by the experimental tests are comparable to those of insulating materials currently adopted, for example the expanded polystyrene (EPS) and the extruded polystyrene (XPS) display C_p value of 1.25 J/(g·°C) and 1.5-1.7 J/(g·°C) respectively. All this confirms the reliability of the recent attention that some researchers devoted to this material. This paper further proves that corn cob could be a viable and profitable material for insulating applications and encourages future studies on this bio-based by-product.

4. Experimental macro-scale tests

4.1 Thermal performance assessment

In order to characterize the performance of the corn cobs as raw material for building insulation, the thermal conductance Λ of different envelopes has been evaluated by considering different corn cob configurations. The experimental tests investigate the thermal behaviour of full-scale building envelope specimens and were realized in a movable hot box (MHB). The MHB apparatus [36] has been developed for laboratory purposes, for the determination of the conductance of insulation panels or even wall envelopes. The MHB adopted for the present study is a cubic box, with about 1m of edge, realized with five oriented strand board (OSB) panels insulated with expanded polystyrene (EPS). The frontal empty face houses the element to be studied. A sketch of the MHB apparatus is showed in Figure 8. In order to heat up air inside the box, a thermal resistance (P3) was adopted. Moreover, in order to ensure a homogeneous air temperature inside the box, a fan (P4) was positioned above the resistance. The empty face (front) of the wall, was studied in order to properly house the element to test. To this regard an internal wooden framework covered by an insulating thermoplastic adhesive profile (P7), connected to the main box (P1), has been realized so as to provide a suitable housing for the element that limits as much as possible the air leakage. The main aim of the box is to create a proper environment for the tests. Specifically, it should ensure a uniform internal temperature at least 10°C higher than the room temperature for the test duration (72 hours).



(c)

Figure 8. Design sketches of the MHB. (a) Global view. (b) Axonometric inner view. (c) Exploded view with indicated the main components.

The MHB prototype have been calibrated and validated for the typical range of thermal conductance expected in the present study. All the details are provided in [36] and the main characteristics of the probes used in the experimental tests are summarized in Table A1 in the Appendix. The tests described in this Section followed procedures prescribed by international standards or validated in previous works. In order to confirm the reliability of the results, the main outcomes of the tests were then compared with those available in literature.

For plane building opaque components, the heat flow meter (HFM) method, can be effectively applied for the measurement of surface-to-surface thermal conductance Λ of the specimen, which can be calculated by the following Eq.(4):

$$\Lambda = q / (T_{si} - T_{se}) \quad (4)$$

where: q is the density of heat flow rate = Φ / A; T_{si}, T_{se} respectively are the interior surface temperature of the building element and exterior surface temperature, both in °C or K; □ is the heat flow rate and A the area crossed by Φ. Since the raw corn cobs are an incoherent material, in order to be able to conduct the tests with a rigid support for the temperature sensors and heat flow meter sensors, the cobs have been introduced in the OSB frame (with inner dimensions 1010×1010×170mm^3) in the front of the hot box (element P9 in Figure 8c). The conductance tests consider eight different configurations (labelled cfg.#0-cfg.#7) displayed in Figure 9 and summarized in Table 4. The stratigraphies of the various configurations are the following:

- cgf. #0: OSB panel (18mm) + air gap (170mm) + OSB panel (18mm);
- cgf. #1: OSB panel (18mm) + corn cobs laid with length along X-dir (170mm) + OSB panel (18mm);
- cgf. #2: OSB panel (18mm) + corn cobs laid with length along Y-dir (170mm) + OSB panel (18mm);
- cgf. #3: OSB panel (18mm) + corn cobs laid with length along Z-dir (170mm) + OSB panel (18mm);
- cgf. #4: OSB panel (18mm) + corn cobs layered laid alternatively with length along X-dir and Y-dir (170mm) + OSB panel (18mm);
- cgf. #5: OSB panel (18mm) + corn cobs layered laid alternatively with length along X-dir and Z-dir (170mm) + OSB panel (18mm);
- cgf. #6: OSB panel (18mm) + corn cobs layers laid alternatively with length along Y-dir and Z-dir (170mm) + OSB panel (18mm);
- cgf. #7: OSB panel (18mm) + ground corn cobs (170mm) + OSB panel (18mm).

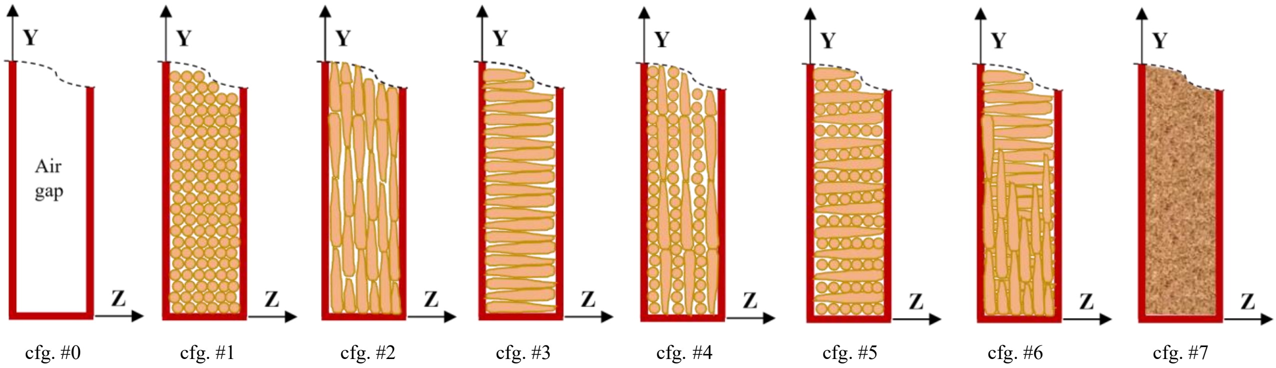


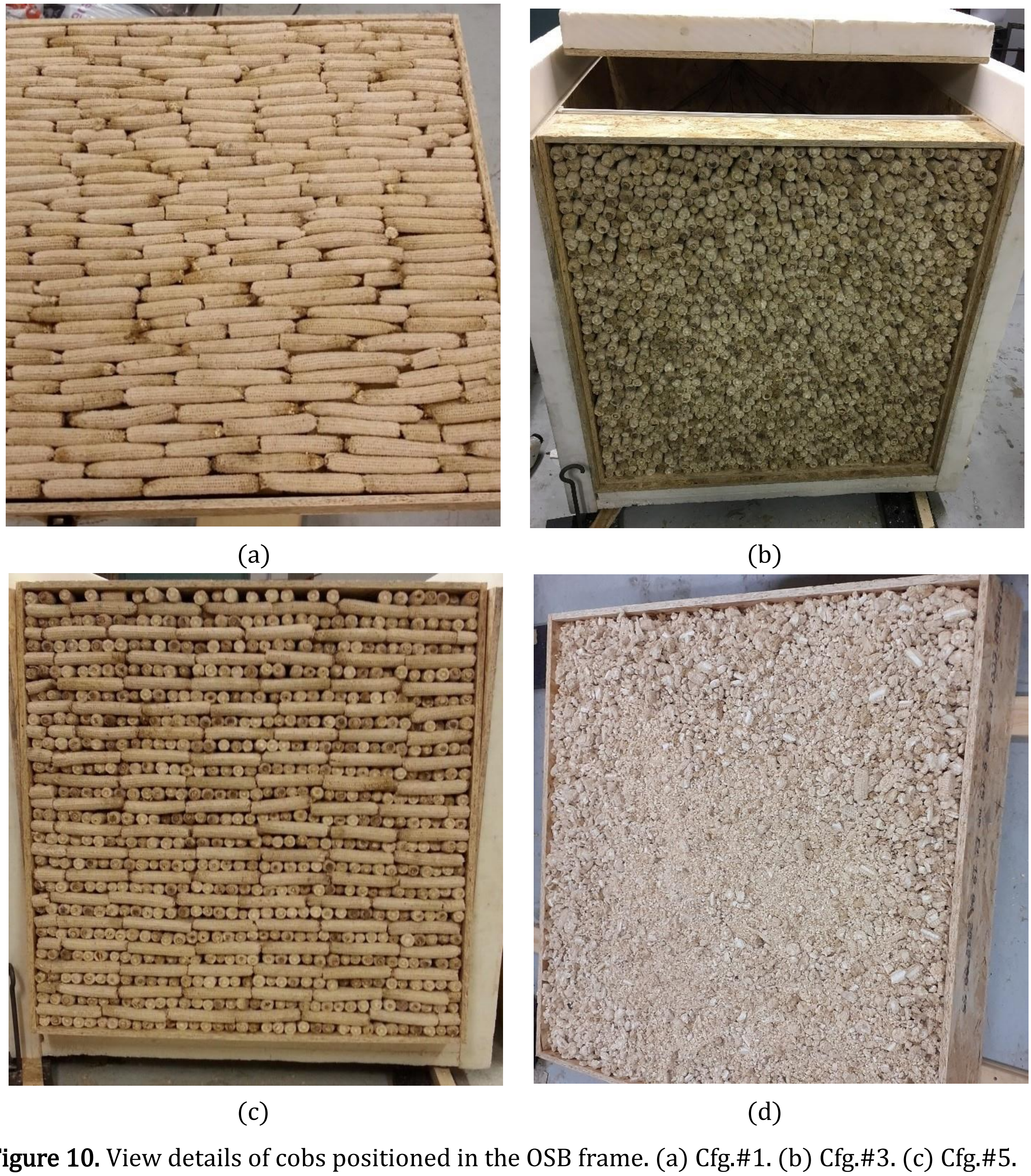
Figure 9. Scheme of the configurations tested in the MHB.

The cfg.#0 has been considered as reference since it is characterized by the empty frame with air inside. The cfg.#1 – cfg.#3 consider raw cobs, laid in the OSB frame, with the cob length in direction X, Y and Z respectively (see Figure 10). The configurations from 4 to 6 consider cobs laid in two layers in the OSB frame and obtained with cobs oriented with length parallel to different directions. In particular cfg.#4 has two layers characterised by cobs oriented parallel to X and Y directions. The cfg.#5 has two layers of cobs oriented in X and Z directions (see Figure 10c). The cfg.#6 has two layers of cobs oriented in Y and Z directions following the scheme in Figure 9.

Table 4. Main results of the configurations tested in the MHB (where: ag is air gap, rc is raw cobs and gc is ground cobs).

Cfg. #	Cfg. label	Sample stratigraphy	Density (Kg/m³)	Λ (W/m²K)	λ_{cob} (W/mK)	Y_{mn} (W/m²K)	f (-)	Δt (h)
0	Air gap	OSB– ag –OSB	-	2.42	-	-	-	-
1	X-dir	OSB– X rc–OSB	195	0.67	0.14	0.39	0.63	6.19
2	Y-dir	OSB– Y rc–OSB	195	0.82	0.17	0.48	0.67	5.69
3	Z-dir	OSB– Z rc –OSB	212	1.13	0.26	0.67	0.71	5.03
4	XY-dir	OSB– XY rc –OSB	198	0.72	0.15	0.42	0.64	6.06
5	XZ-dir	OSB– XZ rc –OSB	212	0.76	0.16	0.43	0.63	6.15
6	YZ-dir	OSB– YZ rc –OSB	212	0.66	0.13	0.34	0.58	6.74
7	ground	OSB–gc–OSB	213	0.62	0.12	0.31	0.56	7.02

Finally, in order to test the thermal behaviour of corn cobs as particulate material, ground cob mixture (with particle dimension in the range 2-30mm after mechanical grinding process) has been laid in the frame realizing the cfg.#7 (see Figure 10d). The latter configuration has been introduced and investigated since it should be the most viable and simple to introduce in an industrial process aiming at marketable production of building insulation applications. Table 4 shows the different content density, calculated as ratio between weight of the content and gross volume of the OSB frame. The differences are very limited and is to attribute to the difficult to properly fill the frame volume in the configurations #1, #2 and #4. This is confirmed by the lower density values for these three configurations.



(a) (b) (c) (d)

Figure 10. View details of cobs positioned in the OSB frame. (a) Cfg.#1. (b) Cfg.#3. (c) Cfg.#5. (d) Cfg.#7.

The data acquired during the test are then elaborated in order to assess the conductance by using Eq. (4) according to the progressive average method. As reported in the ISO 9869-1:2014 [32], this method assumes that the conductance is obtained by dividing the mean density of heat flow rate (q) by the mean temperature difference (T_{si}-T_{se}), the average being taken over a long enough period of time. An estimate of the conductance Λ is then obtained by expression:

$$\Lambda = \frac{\sum_{j=1}^{n} q_j}{\sum_{j=1}^{n} (T_{si,j} - T_{se,j})} \quad (5)$$

where: *j* are the individual measurements and the other quantities are already defined above. As a representative example, Figures 11a-b show the trends of temperature (indoor the hot chamber and outdoor the hot chamber) and heat flow measured at the center of the specimen during the first 24 hours of the experimental test on cfg.#1. It is worth to notice that outdoor temperature is almost constant (between 20 and 22°C) with low variations. On the opposite, the indoor temperature fluctuates between 40°C and 42°C, as expected from the setting of the internal temperature sensors. The oscillating trend on the temperatures is ascribed to the cyclic turning on-turning off of the thermal resistance. For the present tests the temperature difference T_{si}-T_{se} has been always abundantly higher than 10°C (the one suggested by the ISO 9869-1:2014). Moreover, Figures 11c reports the trend of the conductance value that, as expected owing to the MHB dimensions, rapidly (in few hours) point towards the final value - corresponding to the thermal equilibrium configuration - identified with the attainment, within a defined tolerance, of a horizontal asymptote in the conductance curve. The attainment of the horizontal asymptote in the conductance curve can be better evaluated on the graph of the relative difference in Figure 11d plotting for each instant the numerical difference between the conductance values at current step and at previous step divided by the initial conductance value. After 72 hours of test the relative difference, expressed as order of magnitude, is about 1‰ of the initial conductance value confirming a substantial thermal equilibrium.

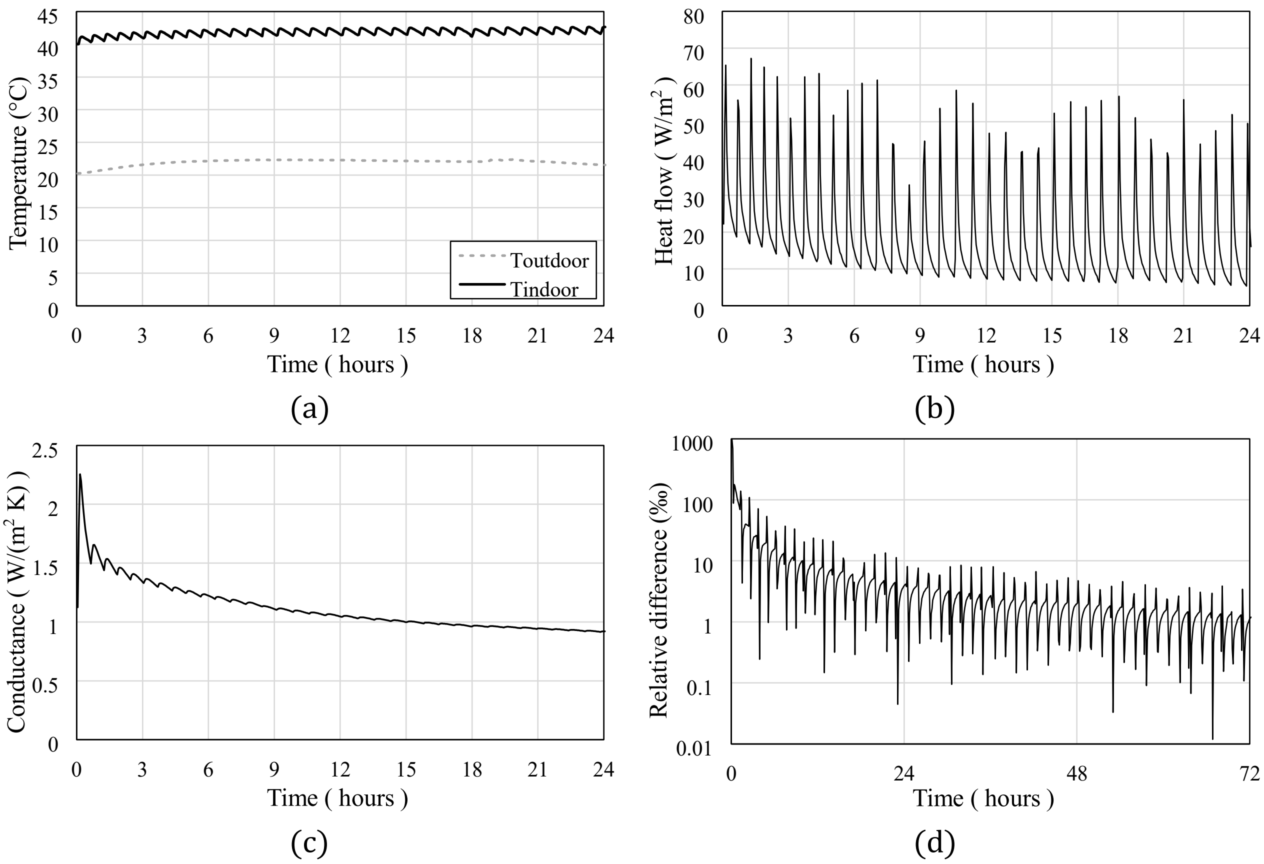


Figure 11. Trend of the main parameters obtained from the experimental test on cfg.#1. (a) Temperatures trend for the first 24 hours from the beginning (where $T_{outdoor}$ is the temperature outdoor the MHB and T_{indoor} is the temperature measured indoor the MHB at the center of the sample). (b) Detail of the typical trends of the heat flow recorded during 24 hours of test. (c) Conductance trend for the first 24 hours from the beginning of the test. (d) Relative difference (per mil) between the conductance values at current step and at previous step divided by the initial conductance value, during the 72 hours of the thermal test.

The final conductance value, obtained for each configuration, is reported in the fifth column in Table 4. Obviously the highest value is obtained for the air gap configuration with a conductance equal to 2.42 W/(m^2·K). This value is not particularly important for the thermal characterization of the corn cob behaviour but provides a sort of upper limit and it was considered as reference value since the conductance reduction obtained for the other configurations can be attributed to presence and orientation of corn cobs filling the OSB frame. The conductance value ranges from 0.62 to 1.13 W/(m^2·K) and it shows that the orientation of the cobs plays a crucial role. The best thermal performance has been obtained with the ground cob, i.e. cfg.#7, and this represents an extremely important results since this configuration is probably the simplest to attain with an industrial process. Comparable conductance values have been obtained for the cfg.#1 and cfg.#6 where the latter has cobs arranged in layers differently oriented and providing a similar resistance to the heat flow.

As expected, the worst thermal performance has been observed for cfg.#3 with cobs oriented with their main axis parallel to the Z direction, i.e. along the panel thickness direction. The poor thermal behaviour is to attribute to the corn cob texture that creates series of horizontal channels facilitating the heat transmission since directly connecting the inner to the outer face of the sample. The other configurations, i.e. #2, #4 and #5, provide an intermediate thermal behaviour but in any way worse than ground cobs sample.

Moreover, as showed in Figure 12, is worth to note the absence of a correlation between content density and thermal conductance cannot be drawn for this material. Indeed, analogous conductance ranges can be obtained with different content density values, and this confirms that cob orientation and texture play the major role for the material configurations considered here.

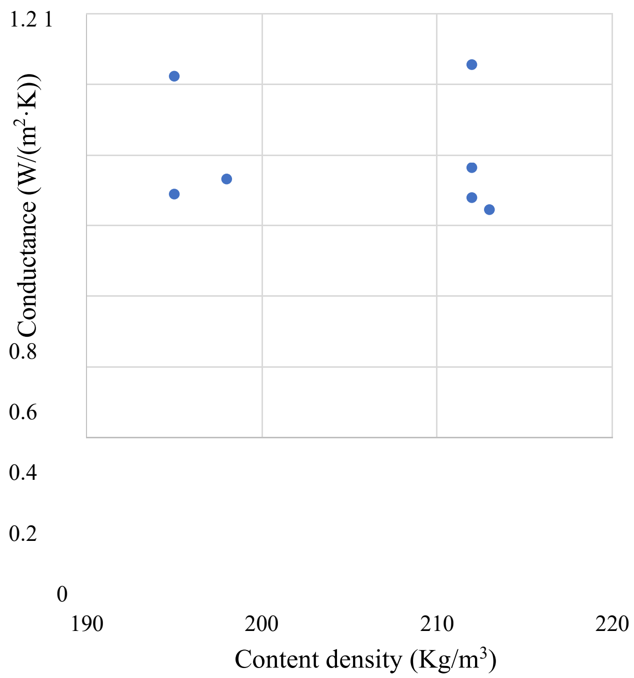


Figure 12. Analysis of the conductance results: independence from the content density.

Furthermore, in the sixth column of Table 4 the values of the apparent cob thermal conductivity □$_{cob}$ are reported. Also in this case, the best performances are showed by the cob cfg. #7 confirming the indications provided by the conductance values.

Finally, in order to evaluate the dynamic thermal characteristics of the different configurations, the evaluation of the periodic thermal transmittance (Y_{mn}), of the decrement factor (f) and of the time lag or time shift (□t) has been realized. The values of the three characteristic have been calculated with the method reported in [37]. As the Table 4 shows, the value of Y_{mn}) ranges from 0.31 to 0.67 W/m^{2}K for the different configurations; the value of the decrement factor goes from 0.56 to 0.71 and the time shift ranges between 5.03 and 7.02 h. Also these analyses confirmed that the best performances are showed by the cob cfg. #7 and provided promising outcomes with numerical values of the same order of magnitude as for commercial products.

Concluding, a similar thermal test conducted on an expanded polystyrene (EPS) panel with commercial thickness t=80mm provide a conductance value equal to 0.53 W/(m^2 K) (for details see [36]). Even if the thickness sample, is different this comparison shows that the corn cob bio-based building insulation applications can represent a viable alternative to the actual commercial materials/panels with good insulation properties but fossil origin, e.g. extruded polystyrene, expanded polystyrene, polyisocyanurate and polyurethane foam, and it should stimulate other possible studies on the way to use renewable agricultural waste products.

Future studies should also investigate issues related to the durability of this material and its fire resistance since these characteristics are very important properties required for the building materials. Some preliminary indications on this last aspect are provided in [16] where the authors reported the results of fire resistance preliminary tests performed on cob samples. Based on these first outcomes, it seems worth to conclude that corn cobs have an acceptable fire resistance when compared with other thermal insulation materials. Further tests will be carried out by the authors in this field but they are out of the scope of this paper.

4.2 Acoustic performance assessment

In order to characterize the acoustic performance of corn cobs, airborne sound insulation tests have been realized. The airborne sound insulation test is probably the most applied in the context of bio-based and recycled products for sound insulation [14] since these materials are very likely to be introduced in both vertical walls and horizontal floors as noise barrier. The experimental tests described in the following subsection have been adopted to evaluate the sound insulation potential of the corn cob as raw material.

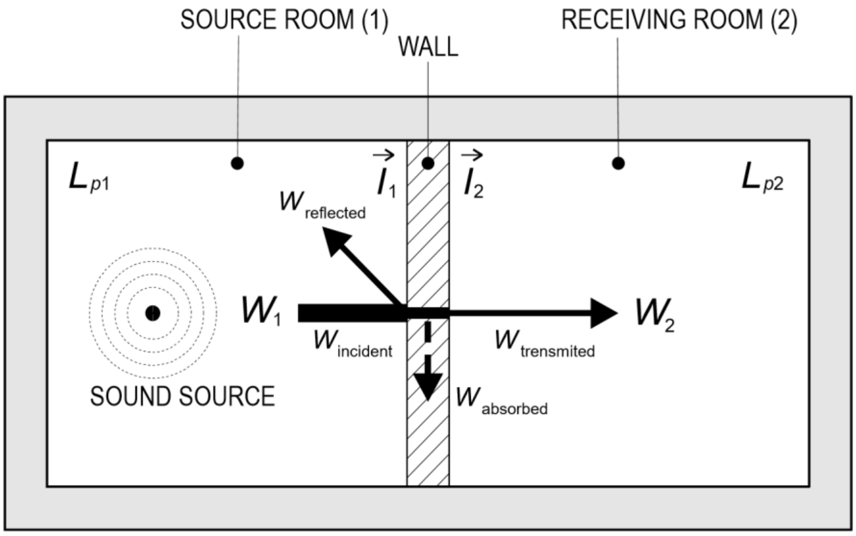
The sound insulation tests have been performed in the Acoustic Laboratory of the Department of Industrial Engineering of the University of Bologna. The tests described in this sub-Section followed procedures prescribed by international standards or validated in previous works and the tests were performed by using certified equipment. In order to confirm the reliability of the results, the main outcomes of the tests were then compared with those available in literature.

The measurements under diffuse field conditions were performed on different lightweight walls characterized by the same perimeter frame and three different vertical stratigraphies: 1 OSB panel, 2 OSB panel with air gap and 2 OSB panel with corn cobs inside the gap.

The wall has been installed in the transmission chambers (see Figure 13) of the laboratory and insulation measurements have been performed according to the standard ISO 10140-2 [38]. The source and measurement positions as well as the measurement procedure are defined by the standard ISO 10140-4 [39] standard. The frequency range analysed is in the one-third of octave band from 100 Hz to 5000 Hz. The sound reduction index R can be evaluated according to the ISO 10140-2 [38] as:

$$R = L_1 - L_2 + 10\log\frac{S}{A}\ (\mathrm{dB}) \qquad (6)$$

where: L_1 (dB) is the energy average sound pressure level measured in the source room; L_2(dB) is the energy average sound pressure level in the receiving room; S is the area of the test opening in which the test element is installed and A is the equivalent absorption area in the receiving room evaluated from Sabine's law. Figure 14 shows the values of R measured for the three different stratigraphies. As for the thermal tests, the stratigraphy with the air gap is considered as base for the assessment of the corn cob contribution. The R trends, for the three different stratigraphies, are rather similar with a significant improvement of the acoustic performance by moving from the solution with 1 OSB layer to the solution with 2 OSB and air gap in the middle.

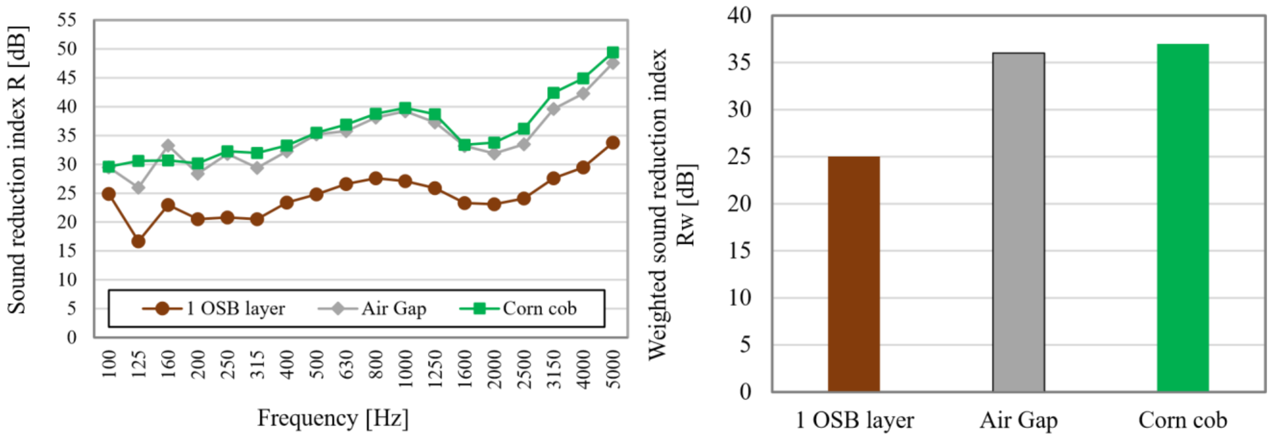


(a)

(b) (c)

Figure 13. Layout of the acoustic room used for the tests. (a) View of the source room. (b) View of the receiving room.

On the other side, at the low-medium frequencies (< 630 Hz) the cob contribution is almost negligible. The cobs provide however a slight improvement also at the medium-high frequencies (> 1000 Hz). In the range of medium-high frequencies the critical frequency of the OSB panels is about 1600-2000 Hz, confirmed also by the configuration with corn cobs. From a practical point of view, the raw corn cobs do not represent an effective sound damping material. Finally, following the procedure in EN ISO 717-1 [40], the weighted sound reduction index R_w has been calculated for the different stratigraphies. The weighted sound reduction index is considered a fundamental parameter for the comparison of different building systems tested in laboratory. This index considers a 1/3 octave band frequency range, between 100 Hz and 3150 Hz, which may not be sufficient for a satisfactory description of the behavior at low and high frequency. To consider the behavior, extended in frequency, with respect to normalized noise spectra (pink noise and traffic noise), the spectrum adaptation terms C and C_{tr} must be introduced. The R_w values obtained are reported in Table 5 and showed in Figure 15b. The R_w value characterizing the wall sample filled with corn cob confirms the low sound-absorbing properties of the material. Thus, conversely from the good performance obtained in [14] investigating a corn cob particleboard, raw corn cob does not represent an efficient material in noise reduction.



(a) (b)

Figure 14. Main results of the acoustic tests. (a) Sound reduction index R. (b) Weighted sound reduction index R_w.

Table 5. Values of weighted sound reduction index, R_w, and spectrum adaptation terms, C and C_{tr}, for the different stratigraphies.

Sample stratigraphy	C	C_{tr}	Rw (dB)
1 OSB layer	-1	-2	25
Air gap	-2	-3	36
Corn cob	-1	-2	37

5. Concluding remarks

The process of replacing fossil-derived materials with alternative bio-based ones is still an open issue, also in the construction sector. In this context and with particular reference to building insulating materials, the evaluation of the main physical and thermo-acoustic properties is certainly one of the aspects having the greatest interest. Among these materials, the corn cob – already adopted in the past centuries in some Mediterranean countries as building insulation material – has been deeply investigated by other researchers but, despite the several research and efforts, corn cob applications as insulation material are still not fully developed and not ready for the market. Specifically, the corn cob is often investigated as a component in composite materials, making the identification of its own specific thermal characteristics almost impossible. Nevertheless, some of those characteristics are necessary to use this material in the building construction sector and literature lacks of studies that analyze them globally.

This paper aimed at filling this gap, investigating the corn cob at different scales and under different disciplines. Firstly, the corn cob was examined at micro scale to identify its chemical composition, structure and some physical characteristics such as density, water absorption and specific heat. Then, it has been studied at macro scale designing and investigating possible constructions (thought to be wall or roof constructions) to assess its thermal and acoustic performances in real applications, identifying the most performing configuration. Under this light, this work suggests a strategy to adopt to evaluate natural materials for building construction purposes.

The paper presents the main results of an extensive multidisciplinary experimental campaign conducted on corn cob-based samples and represents a further contribution to the knowledge of this natural material, up to now mainly considered a maize production waste. With reference to the thermal properties of the material, the specific heat C_p has been evaluated for samples extracted by different corn cob layers. This represents a first attempt to assess this important parameter for the corn cob, in the range 0°C – 40°C, values not currently available in literature. The outer and the middle corn cob layers have C_p values respectively 1.68 J/(g·°C) and 1.72 J/(g·°C) at 20° C. The inner layer has C_p value equal to 2.6 J/(g·°C) for 20 °C. The difference between the inner and middle/outer layers could be attributed to the different morphology and void presence, as indeed observed with the SEM micrographs. The C_p values deduced by the experimental tests are comparable to those of insulating materials currently adopted, such as EPS and XPS.

Finally, the thermal performance of the cobs has been assessed from a macro-scale point of view, by testing six different wall samples filled with cobs laid in different configurations. For each configuration, the wall conductance value (□) has been evaluated by means of a movable hot box. The outcomes of the conductance tests showed that □ value ranges from 0.62 to 1.13 W/(m^2·K) and it means that the orientation of the cobs play a very important role. The best thermal performance has been obtained with the ground cob. This is an extremely important result since this configuration is probably the simplest to provide with an industrial process and thus paves the way for an upscaling of this material in the building field. As last, the sound insulation tests aiming at the characterization of the sound reduction index of walls filled with raw corn cobs have showed that the latter do not represent an effective sound damping material.

This paper further proves the corn cob could be a viable and profitable material for insulating applications and encourages future studies on this bio-based by-product. Future studies will investigate practical applications and must consider and assess the durability, the fire resistance.

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APPENDIX

Table A1. Main characteristics of the probes used in the experimental tests.

Probe	Resolution	Accuracy	Operative range
DHT 22 (Temp)	16-bit	± 0.1°C	-40°C ÷ 80°C
DHT 22 (rH)	16-bit	± 1%	0% ÷ 100%
FE01-3B (Temp)	0.01°C	± (0.01+0.17|t|)°C	-20°C ÷ 60°C
FE01-3B (Heat flux)	$0.01W/m^2$	±5%	$-300W/m^2 \div 300W/m^2$