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A review of unconventional sustainable building insulation materials

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ABSTRACT

Building insulation is commonly realized using materials obtained from petrochemicals (mainly polystyrene) or from natural sources processed with high energy consumptions (glass and rock wools). These materials cause significant detrimental effects on the environment mainly due to the production stage, i.e. use of non-renewable materials and fossil energy consumption, and to the disposal stage, i.e. problems in reusing or recycling the products at the end of their lives. The introduction of the concept of "sustainability" in building design process encouraged researches aimed at developing thermal and acoustic insulating materials using natural or recycled materials. Some of them, such as kenaf or wood fiber, are already commercialized but their diffusion could be further improved since their performance is similar to the synthetic ones. Others are currently under study and their development is only at an early stage. The goal of the paper is to report a state of the art of building insulation products made of natural or recycled materials that are not or scarcely commercialized. Comparative analyses were carried out considering in particular thermal characteristics in terms of thermal conductivity, specific heat and density. Data on the acoustic performance of the materials were also reported. Life Cycle Assessment data were finally collected, in order to put in evidence the environmental advantages of these materials. Particular attention was paid to researches focused to exploit local materials and even industrial byproducts, since these approaches respectively limit transportation and disposal impacts.

1. Introduction

One of the most important challenges of future buildings is the reduction of energy consumptions in all their life phases, from construction to demolition. The United Nation Environment Program [1] estimates that buildings consume about 40% of the world global energy, 25% of the global water, 40% of the global resources; buildings are also responsible of about 1/3 of greenhouse gas emissions of the whole planet. Similar values were observed by studies performed by the U.S. Department of Energy [2] and by the European Commission [3]. In Europe, this situation fostered the definition of several environmental policies: the most important ones are the Energy Performance of Building Directive (EPBD, [4]) and the Energy Efficiency Directive (EED, [5]). European Commission estimated that these actions will contribute to reduce the energy demand for heating and cooling purposes by 8% in 2020, 12% in 2030 and 17% in 2050 compared to 2005 data. Fig. 1 reports the trend of the European energy demand in the residential sector from 2000 to 2050 (data over 2013 are estimations) [6]. Strategies for the

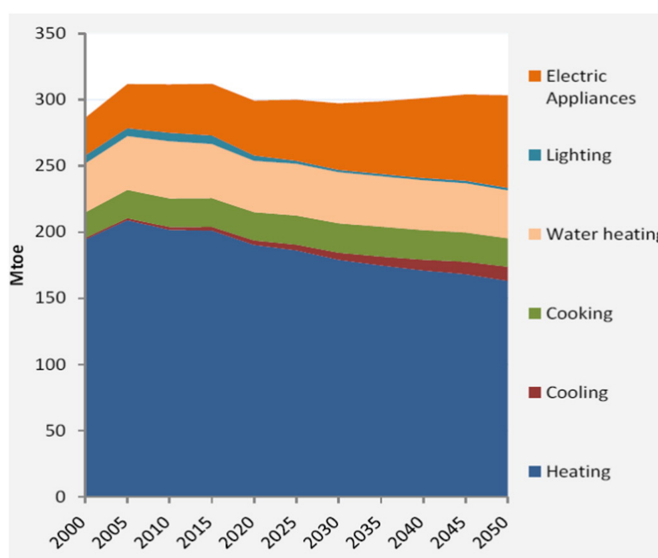

Fig. 1. Trend of the European energy demand in the residential sector by energy use [6].

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reduction of heating and cooling demands are focused not only on improving appliance efficiency or modifying citizen life styles, but also on enhancing the insulation properties of building envelopes. The latter action could play a decisive role since it can lead to significant improvements with a low pay-back time [7–10]. The importance of increasing the thermal performance in the building sector was also highlighted by a comparative analysis about energy production and consumption estimations. The study evidences that in 2035 about the 75% of energy production will be produced from fossil fuels. In order to reduce adverse environmental impacts the most interesting strategy is represented by investments aimed at increasing energy efficiency in the building sector, since about four-fifth of its potential was estimated to be unexploited in 2012 [11]. Using efficient insulation materials is also important to reduce the impact of urban noise; about 65% of European citizens are estimated to be exposed to noise levels for which adverse effect on health can be expected [12]. A detailed analysis of these impacts on citizens is reported in [13]. Unfortunately the use of natural or recycled materials for these purposes is not particularly widespread: a 2012 analysis reports that in 2011 mineral wool (52% of the market share) and plastics (41%) prevailed in the world thermal insulating materials market [14]. Their use can cause environmental issues due to the consumption of non-renewable materials and to the disposal phases of end-of-life products, in particular for plastics. The introduction of the concept of "sustainability" in the building sector gradually led to the production of insulation products made of natural or recycled material; some of them are already present in the market while others are still at an early stage of production or study. These approaches could be particularly important and useful in developing countries, which do not have well-defined recycling policies and are affected by disposal issues due to large quantities of agricultural and industrial by-products. However actions aimed at reducing the environmental impacts of the building sector should not only be addressed at enhancing thermal insulation properties of buildings envelopes, but also at a better energy optimization at an urban level; for instance the importance of teleheating systems, cogenerative smart grids and high energy efficiency technological systems was proven in detail by recent studies [15,16].

The main goal of the paper is to report a state of the art of innovative thermal and also acoustical insulating materials realized using natural and/or recycled materials whose development is only at an early stage or whose sales are still limited. After a brief description of each material taken into account, the study reports the parameters which are usually requested by building designers for the characterization of thermal insulation materials (density, thermal conductivity, specific heat) and acoustic materials (sound absorption and sound insulation properties). A brief analysis about fire and vapor resistance and sustainability of each material is finally reported.

2. Thermal, acoustic and environmental properties

2.1. Thermal insulation

Thermal insulation systems and materials aim at reducing the transmission of heat flow. The thermal insulation performance of single or combined homogeneous materials is usually evaluated respectively through thermal conductivity and thermal transmittance. Thermal conductivity λ defines the steady state heat flow passing through a unit area of a homogeneous material, 1 m thick, induced by a 1 K difference of temperature on its faces. It is expressed in W/mK and it is measured in compliance with EN 12664 (low thermal resistance) [17], EN 12667 (high thermal resistance) [18], EN 12939 (thick products of high and medium thermal resistance) [19] or also ASTM C518 [20]. A material is usually considered as a thermal insulator if its conductivity is lower than 0.07 W/mK.

Thermal transmittance, also known as U-Value, is the steady state heat flow passing through a unit surface area induced by a 1 K difference of temperature and it takes into account also convective and radiative heat transfers. It is expressed in W/m^{2}K and it is measured with the hot-box method [21–24]. Thermal transmittance can also be estimated with the ISO 6946 calculation method [25], but several comparative studies demonstrated that the calculated U-values are usually lower than the measured ones [26,27]. Thermal conductivity and transmittance are used to define the insulation properties in steady state; for the unsteady the most used parameter is the thermal diffusivity D, that allows to compare the ability of materials to conduct and store thermal energy. It is given by the ratio of thermal conductivity and the product of density and specific heat. It is expressed in m^2/s and it is measured in compliance with ISO 22007-1 [30]. The specific heat defines a material's ability to store energy: it is the heat required by 1 kg of material to modify its temperature of 1 K and it is expressed in J/kgK. A material characterized by a high value of specific heat can provide low diffusivity values even with low density. Insulators characterized by thermal conductivity under 0.05 W/mK and specific heat over 1.4 kJ/kgK can be considered very performing even in unsteady state conditions.

The importance of the evaluation of thermal performance in buildings using approaches more accurate than the steady state one was proved also in [28]. The study reports the outcomes of an analysis carried out comparing building energy consumptions using the more accurate semi-stationary and dynamic methodologies calibrated through in situ measurements. The most reliable results were obtained using the dynamic methodology, thanks to a better estimation of solar gains. The importance of a proper evaluation of thermal inertia using dynamic approaches was deeply discussed also in [29].

Another parameter that deeply affects buildings thermal performances is the albedo of the roof that is measured in compliance with ASTM E1918 [31]. Albedo is defined as the component of solar radiation reflected from an object back into space. A recent study has also studied the potential of using spaceborne data to locate areas where this parameter should be increased using more reflective surfaces [32]. This approach can be used in urban plans to tackle heating issues in buildings.

2.2. Acoustic properties

Airborne sound insulation is expressed by the weighted sound reduction index R_w, as defined by EN ISO 717-1 [33]. The sound reduction index defines the ability of a structure (wall, roof, window, etc.) to prevent the passage of sound through itself and it is expressed in dB. The higher the sound reduction index, the higher the sound insulation of the structure. Sound insulation properties of a sample are evaluated through phonometric measures performed in compliance with ISO 10140 [34]. The R_w is calculated on real-sized samples, such as windows, doors, partitions etc. The ability of a sample to limit the transmission of sound can be evaluated for small sized samples by means of an impedance tube and it is expressed as Transmission Loss TL [35]. The ability of materials and systems to dissipate the incident acoustic energy is assessed by the sound absorption coefficient α. It is defined as the ratio between the absorbed and the incident sound power. The sound power absorbed by a material is usually evaluated by Eq. (1).

$$W_a = W_i - W_r - W_t \quad (1)$$

$$\alpha = \frac{W_a}{W_i} \quad (2)$$

where: W_i is the incident sound power, W_r the sound power reflected by the analyzed material, W_t the sound power that passes through the material and W_a is the absorbed sound power.

This parameter can be measured for small samples using an impedance tube in compliance with ISO 10534-2 [36] or, for bigger samples (at least 10 m^2), in a reverberation room as defined by ISO 354 [37] or by ASTM C423-09a [38]. These two methods define two different kinds of absorption coefficients, respectively for normal incidence and random incidence of sound. Sound absorption properties could be also

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defined through a single rating system such as NRC and SAA [38]. The first one is the arithmetic average of the absorption coefficients measured in the octave bands between 250 and 2000 Hz, the second considers a wider range, from 200 to 2500 Hz, and third octave bands. Some materials are used to insulate from impact sounds, for instance to reduce the sound of footsteps coming from people walking on a floor structure; these materials are commonly resilient layers used in floating floors. The parameters used to assess this ability are the dynamic stiffness s_t [39]) and the weighted sound reduction index ΔL_W [40].

2.3. Life Cycle Assessment

Life Cycle Assessment (LCA) is a methodology to evaluate the impacts of products and services on the environment and on human health during their entire life; this approach is also called *cradle to grave* since the evaluation is performed from the extraction of raw materials to the disposal of the exhaust product. The *cradle to gate* approach is used when the assessment of the product ends before the transportation to costumers. A correct LCA analysis is performed in compliance to the ISO standards 14040 [41] and 14044 [42]. The procedure requires the definition of the system boundary since all environmental burdens not comprised within are not considered. In LCA analysis all processes and impacts are normalized with respect to a quantity named functional unit; for the evaluation of thermal insulation materials it is usually the mass of material needed to obtain a thermal resistance of 1 m^2K/W. The environmental burden is measured using well-defined indicators such as the Cumulative Energy Demand (CED) and the Global Warming Potential (IPPC GWP 2007). The first is the primary energy consumed during the whole life cycle, measured in MJ per functional unit. The second one is a method defined by the Intergovernmental Panel on Climate Change (IPCC) to evaluate the greenhouse gas emissions due to the functional unit of the studied material during its life cycle. The indicator is evaluated in terms of kilograms of equivalent CO_2 per functional unit on three time horizons (20, 50 and 100 years). Examples of applications of LCA to real case studies can be found in [43–45].

2.4. Other properties

The reaction to fire of a material can be evaluated using the rating system defined by [46]. It classifies the reaction to fire considering several parameters such as the temperature increase, mass loss rate, heat release, smoke production, etc. The best performing, non-combustible, materials are classified A1 while the worst one are classified E. Additional classes are also defined to characterize the smoke development and the burning droplets.

The ability of a material to be not permeable to water vapor is measured by water vapor resistance (μ-value, dimensionless). The lower the value the higher the material vapor permeability. The μ-value value of 1 is assigned to air. EPS building insulators are characterized by a μ-value between 20 and 70, while coir-based materials are between 5 and 30. Mineral wools are characterized by very low values (under 5) whereas vapor barriers can reach values over 100,000.

3. State of the art of unconventional building insulation materials

The thermal and acoustic insulation properties of some green materials and of some agricultural and industrial by-products were studied by several authors in order to assess the opportunity to re-use or recycle them in the building sector. The use of these products is not widespread

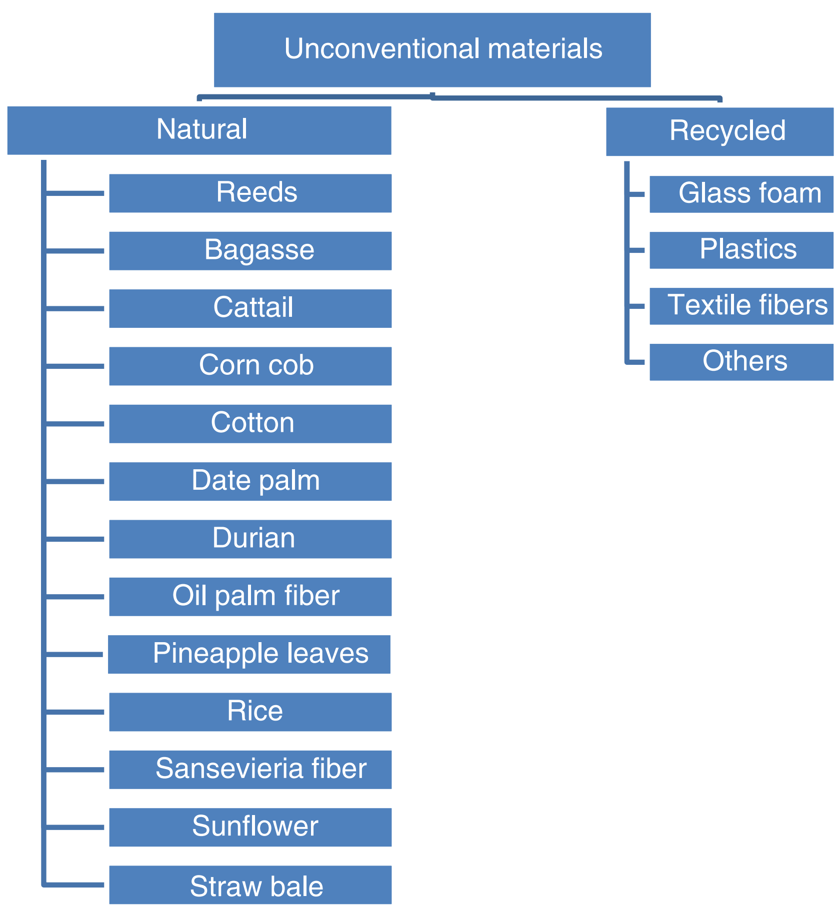

Fig. 2. Block diagram of the analyzed unconventional building insulation materials.

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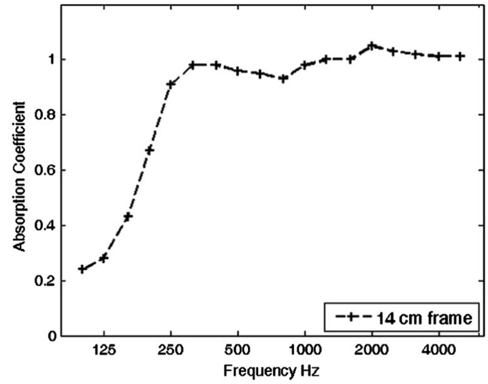

Fig. 3. Reed panel [53] (left) and sound absorption coefficient of a 14 cm thick sample measured in a reverberation room [51] (right).

and, in some cases, it is limited to an experimental and laboratory stage. A review of these materials is summarized in the present section, which reports for each material the most important thermal and acoustic parameters and the source of the data (Fig. 2). The actual sustainability of the considered insulation materials is linked to their availability; they should be used preferably where they are harvested, produced or manufactured. The paper is mainly focused on the thermal insulation performance. A deeper investigation about the acoustical properties of sustainable materials is reported in [47]. Where available, data concerning the environmental performance measured through LCA approach are reported. Nevertheless the latter information is usually not provided since the majority of unconventional materials is only at a prototypal stage. Data concerning the 1993–2013 average world production of each one of the analyzed materials are reported in FAO official statistics [48].

3.1. Natural

3.1.1. Reeds

Reeds used in the building sector are mainly obtained from *Phragmites australis*, a plant usually harvested in winter season and put together with iron or nylon wires in panels (Fig. 3). Reed is not properly an unconventional building material since some reed panels can be found in the market and they are used in roofs and walls, both as internal or external insulation covered with plaster. However their use is not very widespread except where there is abundance of this material (Eastern Europe in particular). The thermal conductivity of a reed panel is between 0.045 and 0.056 W/mK, the density varies from 130 to 190 kg/m^3 and the specific heat reaches a maximum value of 1200 J/kgK [53,109–111]. Nevertheless a 0.045 W/mK [109] value of thermal conductivity seems to be too low; measures performed by the Authors by means of hot plate method gave values around 0.055 W/mK [49]. The sound absorption coefficient of reeds was firstly investigated in detail by Chilekwa et al. within the activities of Holiwood project. They also studied the influence of the reed configuration on the performance of some samples using the impedance tube method. Samples in which reeds are placed orthogonally to the incident sound were characterized by an absorption coefficient higher than 0.5 for all the frequencies higher than 300 Hz (Fig. 3) [50]. The good acoustic properties were confirmed also by tests realized in reverberation room on a 12 m^2 wide sample [51] and by surveys submitted to subjects placed in a test room (in this case reed were taken from *Arundo donax* plant) [52]. A recent study of the Authors has confirmed that if properly designed, reed panels can represent a sustainable and low cost alternative to common absorbers [49].

3.1.2. Bagasse

Bagasse is one of the most important residues of sugar production and it is currently mainly managed as a waste (Fig. 4). Its great availability in areas where sugar cane is cultivated, its low price and also its content of cellulose that helps reducing the use of synthetic binders, fostered several research works to develop innovative thermal insulation particleboards made of this material. Manohar et al. studied the effect of density the apparent thermal conductivity (evaluated in compliance with ASTM C518 [20]). Samples characterized by density between 70 and 120 kg/m^3 were analyzed. The most performing one was characterized by a density of 100 kg/m^3 and a thermal conductivity of 0.046 W/mK [55,56]. Denser binderless samples were tested by Panyakaev and Fotios that also report the cellulose content of the tested bagasse (76.31%). The thermal conductivity value rises from 0.049 W/mK for the 250 kg/m^3 dense particleboard to 0.055 W/mK of the 350 kg/m^3 dense one [57]. The sound absorbing properties of

Fig. 4. Sugarcane (left) and sugarcane bagasse (right).

Fig. 5. Cattail plant (left) and cattail fiber panels [61] (right).

12 mm thick mats realized mixing bagasse fibers with a binder, were studied recently by Doost-hoseini et al. The analyzed samples were characterized by different density values (300, 400 and 500 kg/m^3), binders (urea–formaldehyde and melamine–urea–formaldehyde) and composition (homogeneous or three layers). The most performing samples were the 400 kg/m^3 homogeneous mats bound with urea-formaldehyde and the 500 kg/m^3 multi-layered one bound with melamine-urea-formaldehyde; in both cases an absorption coefficient higher than 0.5 was observed for frequencies higher than 1000 Hz through the impedance tube method [58]. Another potential use of sugar cane bagasse was tested by Onésippe et al. adding these fibers to a cement composite; the measured thermal conductivity decreased from 0.62 to 0.46 W/mK adding only the 3% of fibers [59]. The average sugar cane world production in the period 1993–2013 is 1.420 × 10^{12} kg, mainly produced in the Americas (49.7%) and Asia (41.6%) [48].

3.1.3. Cattail

Cattails are plants belonging to *Typha* genus considered as a weed with negative effects for other crops (Fig. 5). These plants grown in wetland areas and their control can be difficult due to their rapid growth. Tropical South-East Asian and Pacific North-American areas are the most affected by these weeds. Thermal insulation particleboards made of cattail fiber were studied by Luamkanchanaphan et al. to find a useful use of this plant. The fibers were brought together by a Methylene Diphenyl Diisocyanate binder. The thermal conductivity of the panels was between 0.0438 and 0.0606 W/mK for density between 200 and 400 kg/m^3 [60]. Another research performed by Fraunhofer Institute allowed to design a thermal insulation panel made of cattail fiber characterized by a thermal conductivity of 0.052 W/mK [61]. Finally, a patent for producing an insulation material made of cattail fibers was already published in the USA in 1962 [62].

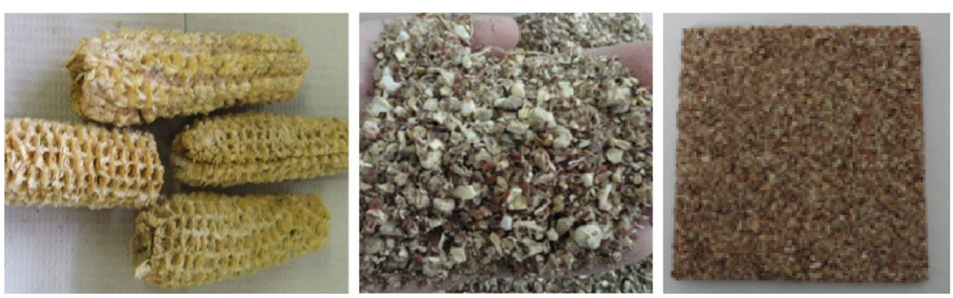

Fig. 6. Corn cob. Raw (left), ground (middle) and panel (right) [63,65].

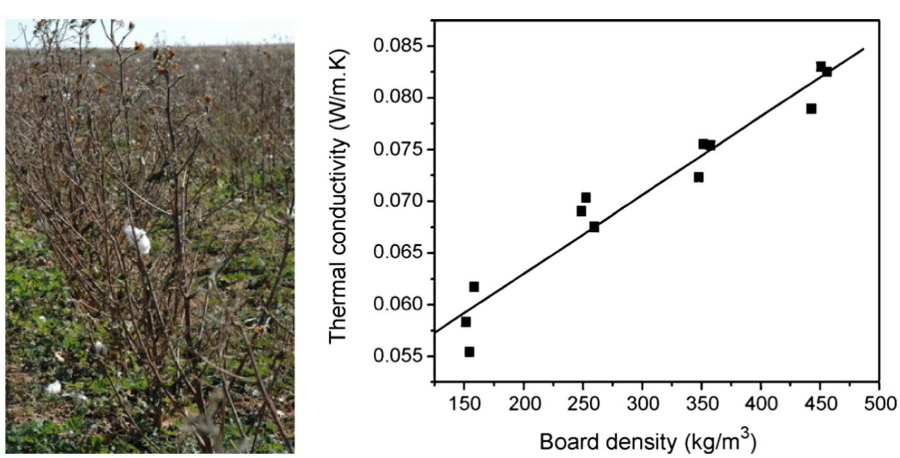

Fig. 7. Cotton stalks and thermal conductivity values vs. board density of samples tested in [66].

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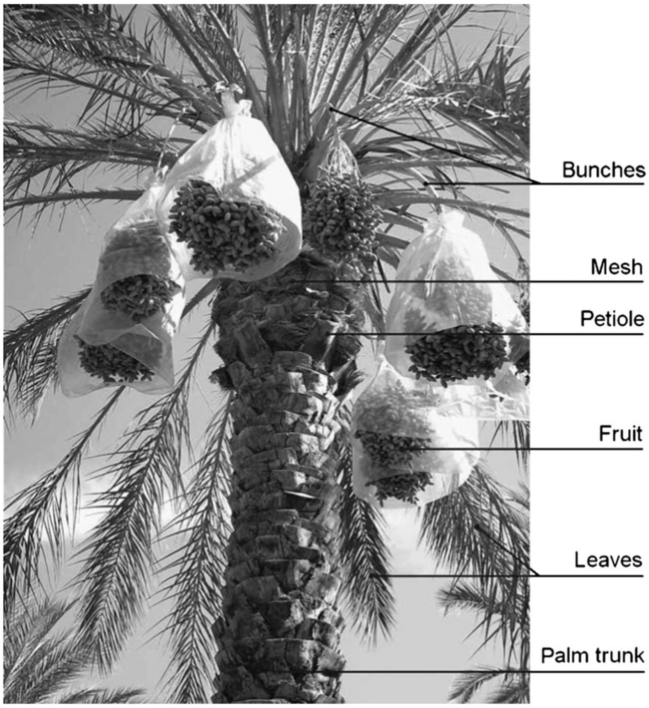

Fig. 8. Date palm elements [67].

3.1.4. Corn cob

Corn cobs are the residuals of corn plants and processing industry. Pinto et al. discovered that some Portuguese *tabique* buildings (a construction technique widespread in Portugal between XVIII and XIX centuries) were realized using corn cobs and earth as filling materials. This mixture was realized mainly to recycle this agricultural waste rather than to improve the thermal insulation properties [63]. The thermal conductivity of particleboards made of ground corn cobs and wood glue (Fig. 6) was estimated in [64] and in [65], but the best value was still too high (0.101 W/mK) to consider this material as a proper thermal insulator. The average maize world production in the period 1993–2013 is of 6.97×10^{11} kg, mainly produced in the Americas (53.1%) and Asia (28.2%) [48].

3.1.5. Cotton stalks

Cotton is the most widespread non-agricultural cultivation used mainly for fabric production. A study carried out by X. Zhou et al. tested the thermal performance of an innovative material realized using the cotton stalks, a residue of cotton production. Particleboards were obtained transforming the stalks in fibers without using chemical binders. The thermal conductivity of the tested sample was between 0.0585 and 0.0815 W/mK (Fig. 7); the denser the material, the lower the thermal insulation [66]. The average cotton lint world production in the period 1993–2013 is 2.14×10^{10} kg, mainly produced in Asia (63.7%) and in the Americas (24.6%) [48].

3.1.6. Date palm

The date palm (*Phoenix dactylifera*) is cultivated in semi-arid areas for the dates production. The residues, such as leaves, petioles (13 per plant per year) and bunches (7 per plant per year) are commonly considered as waste (Fig. 8). According to FAO official data, Agoudjil et al. estimated that about 1,200,000 tons of petioles, 410,000 of leaves and 300,000 of bunches are produced every year worldwide. The great availability of these materials suggested to the author to test the thermal insulation properties of these materials, after their transformation in fibers. Six samples were tested to consider the effect of palm date type and the difference between petioles and bunches-based material. Also the direction of the fiber was tested. The most performing materials was characterized by a thermal conductivity of 0.072 W/mK [67]. In order to evaluate new recycling processes for these materials, also an innovative bio composite material made of gypsum and date palm fiber was studied. It was characterized by a thermal conductivity between 0.15 and 0.17 W/mK and a density of 753 kg/m^3 [68]. The average date world production in the period 1993–2013 is 6.35×10^9 kg, mainly produced in Asia (63.5%) and Africa (35.9%) [48].

3.1.7. Durian

Durian is one of the most widespread fruit in South East Asia, particularly in Thailand; in 2010 the Malaysian Minister of Agriculture declared a production exceeding 300,000 tons. It is harvested from several tree species belonging to the genus Durio (Fig. 9). Khedari et al. evaluated the thermal insulation properties of 9 samples of particleboards made of durian peel with different values of density and types of binder. The most performing one was characterized by a thermal conductivity of 0.064 W/mK and a density of 428 kg/m^3 [69,70]. The thermal conductivity of particleboards made of a mixture of durian and coir fiber was studied in [71] where the lowest value of this parameter, 0.0728 W/mK, was measured for a sample characterized by a density of 330 kg/m^3 and a 50% durian peel fiber content.

3.1.8. Oil palm fiber

Several researches were carried out to recycle residues of the oil palm (*Elaeis guineensis*), a crop cultivated in 11 million hectares worldwide (meanly West Africa, South-East Asia and South America). The most interesting works in this field are collected in [72] where the opportunities of using the bunches of the plant to produce fibers are reported (Fig. 10). The effect of density on the thermal conductivity of oil palm fiber sample was investigated in 2012 by Manohar [56]. The lowest thermal conductivity value was 0.055 W/mK for the 100 kg/m^3 dense specimen. The thermal and physical properties of a structural material made of 40% of oil palm bunch fiber and phenolformaldehyde were studied by Singh et al. The sample developed within the research activity was characterized by a thermal conductivity of 0.293 W/mK and

Fig. 9. Durian plant (left) and fruit (right).

Fig. 10. Empty fruit bunches (left) and oil palm fibers (right).

a thermal diffusivity of 0.158 mm^2/s [73]. The average oil palm fruit world production in the period 1993–2013 is of 1.59×10^{11} kg, mainly produced in Asia (83.5%) [48].

3.1.9. Pineapple leaves

Pineapple collection and manufacturing produces some residues; one of them is constituted by their leaves that are currently treated in energy plants or simply burned. The air and soil pollution due to these processes causes environmental problems that could be limited by finding an innovative use of this material in the building sector. Tangjuank studied the thermal insulation properties of a panel made of shredded and dried pineapple leaves bound using natural rubber latex. The tested samples had density between 178 and 232 kg/m^3 and thermal conductivity between 0.035 and 0.043 W/mK. A lower conductivity value was observed for the sample having a density of 210 kg/m^3. The fire resistance was evaluated using the method defined by the ASTM D 635-98; the less thermal conductive material showed the best performance (1.35 min.). The main results of these measurements are reported in Fig. 11 [74]. Another research by Kumfu et al. investigated the thermal conductivity of a board made of pineapple leaf fibers and natural rubber by means of the hot pressing technique: in this case a 338 kg/m^3 dense sample showed a thermal conductivity of 0.057 W/mK [75]. The average pineapple world production in the period 1993–2013 is 1.73×10^{10} kg, mainly produced in Asia (48.6%) and in the Americas (34.1%) [48].

3.1.10. Rice

FAO 2013 official data states that rice is the third most produced commodity in the world after sugar cane and maize with a production of more than 740 million tons per year [48]. As a consequence a large amount of residues is produced causing disposal concerns, whereas they could be used successfully for the production of useful green materials. Yarbrough et al. evaluated the thermal insulation performance of particleboards made of rice hulls, an important by-product of rice cultivation. The thermal conductivity at 24 °C was between 0.0464 and 0.0566 W/mK; the lowest value was measured for the 154 kg/m^3 dense specimen [76]. The same research work reports the results of thermal insulation tests performed on particleboards made of pecan shells, but the results showed that this material is not adequate for insulation purposes (0.0884 W/mK). Fig. 12 reports the sound absorption coefficient of three composite materials made of rice straw and wood measured in a reverberation room. Straw 0.4, 0.6 and 0.8 are samples containing respectively 10, 20 and 30% of rice in weight. The wood panel manufactured with the addition of 10% rice straw is characterized by a sound absorption coefficient higher than those obtained for particleboards, fiberboard and plywood panels [77]. The average rice world production in the period 1993–2013 is of 6.25×10^{11} kg, mainly produced in Asia (90.9%) [48].

3.1.11. Sansevieria fiber

The thermal insulation properties of an innovative material made of sansevieria fiber reinforced with polyester were studied in [78]. This fiber is obtained from the *Sansevieria roxburghiana* plant, quite common in the tropical areas, with the exception of South America (Fig. 13). The measurement proved that adding sansevieria fiber, the thermal conductivity of the composite material decreased, but the lowest value observed, 0.183 W/mK, still remains high and not suitable for building insulation. Moreover this value was obtained for a sample having only 40% of natural fiber. The thermal conductivity of the pure fiber is lower, 0.132 W/mK, but still unsatisfactory [79].

3.1.12. Sunflower composite materials

The sunflower (*Helianthus annuus*) is one of the most cultivated crops in the world, due to the high oil content of its seeds. Several

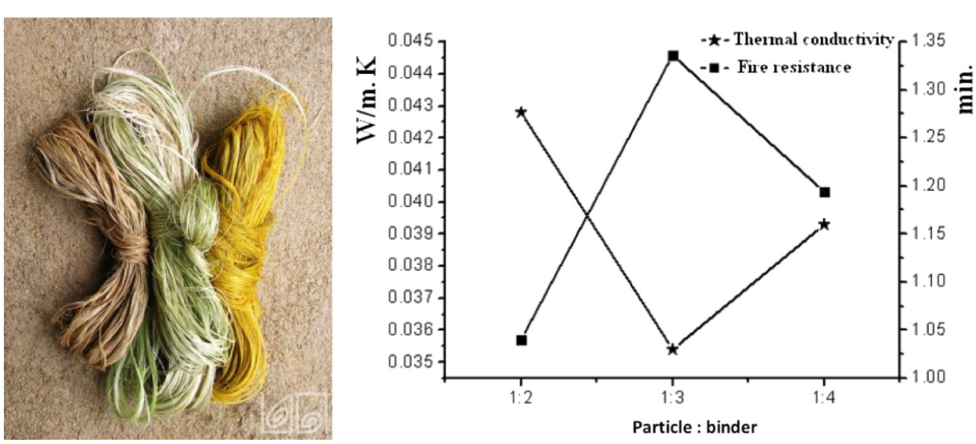

Fig. 11. Pineapple leaf fiber (left) and thermal conductivity values of the samples tested in [74].

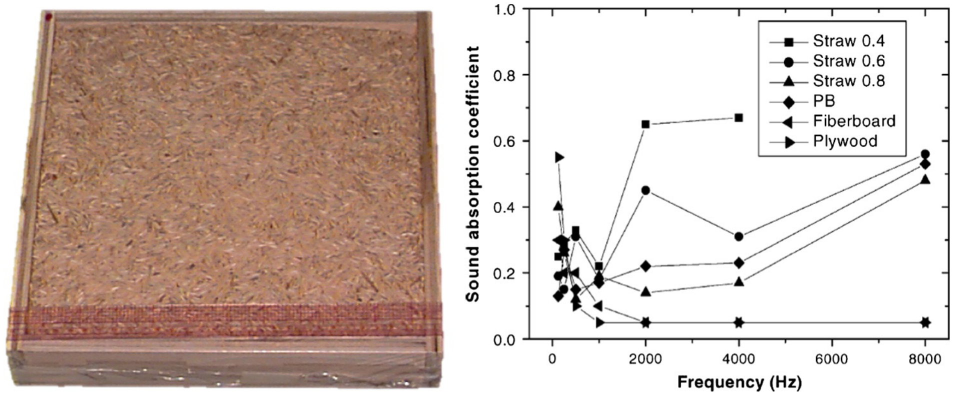

Fig. 12. Thermal insulation panel tested in [76] (left) and sound absorption coefficient (right) of the composite materials made of rice straw and wood tested in [77].

Fig. 13. Sansevieria plant (left) and fiber (middle). On the right, thermal conductivity trend vs. temperature measured in [78].

researches were carried out to develop innovative thermal insulation materials made of plant cultivation or oil production residues. Thermal conductivity of particleboards realized using ground sunflower piths were measured in [80] varying material density and grain size diameter. The lowest value was obtained for the less dense material, 36 kg/m^3, characterized by grain size diameter lower than 1 mm (Fig. 14). In [81] the cake produced during sunflower refinery processes was used to produce a thermal insulation fiberboard: nevertheless the most performing sample was quite fragile and characterized by a high thermal conductivity, 0.0885 W/mK. Finally, the stalks of this plant were used to produce two composite materials containing also textile waste. The two materials differ for the binder, gypsum or epoxy: the measured thermal conductivity was respectively equal to 0.1642 W/mK and 0.0728 W/mK [82]. The average sunflower seed world production in the period 1993–2013 is 2.9×10^{10} kg, mainly produced in Europe (58.0%) and in the Americas (21.1%) [48].

3.1.13. Straw bale

Straw is a byproduct of cereal cultivation that is available in large quantities and at low cost in a great number of countries. Straw has been one of the first materials to be used in green buildings and there are plenty of buildings constructed using this technique all over the world. Usually the straw used for building application derived from wheat cultivation. Several research works evaluated the effects of using straw bale as a thermal insulator in buildings. A thermal characterization of the material was performed by Goodhew et al.; they measured a thermal conductivity of 0.067 W/mK, a diffusivity of $18.2 * 10^7$ m^2/s and a specific heat capacity of 600 J/kgK for a 60 kg/m^3 dense sample [83]. Lower thermal conductivity values were measured for similar samples in [84] and in several analyses collected by the Aalborg University in [85]. The latter study also reported that samples made with the stalks of straw perpendicular to the heat flow have better thermal insulation properties. Some studies evaluated the

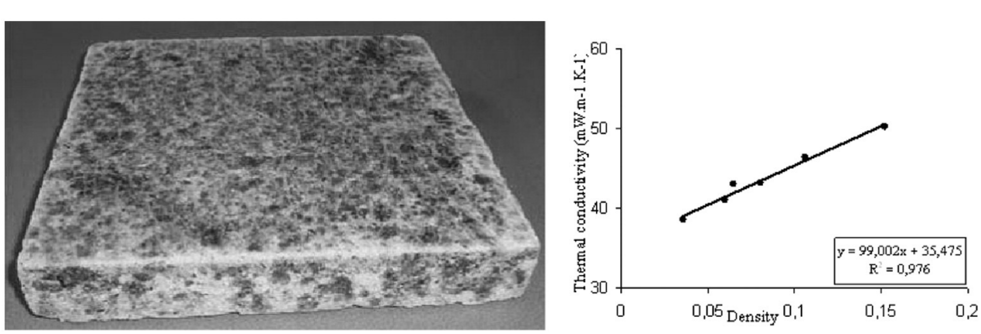

Fig. 14. Sunflower pith agromaterial tested in [80] (left); thermal conductivity trend vs. material density (right).

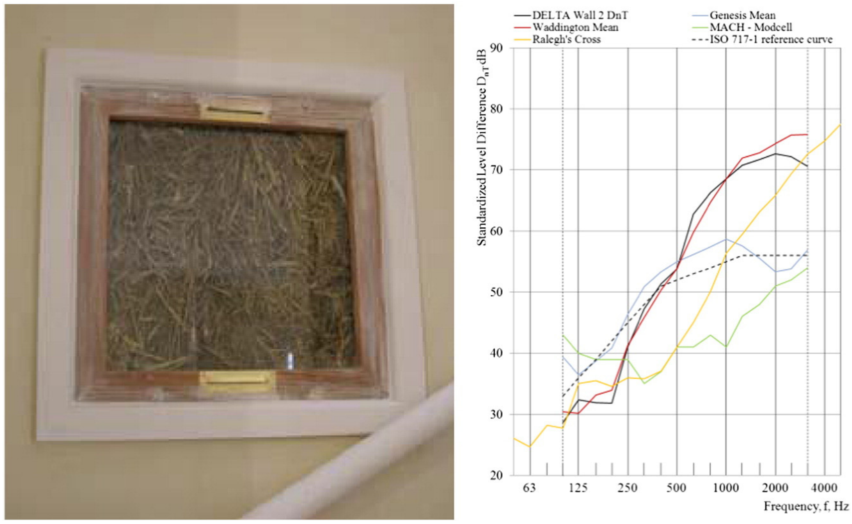

Fig. 15. Viewing panel of a straw bale wall (left); results of the sound insulation tests performed in [87] (right).

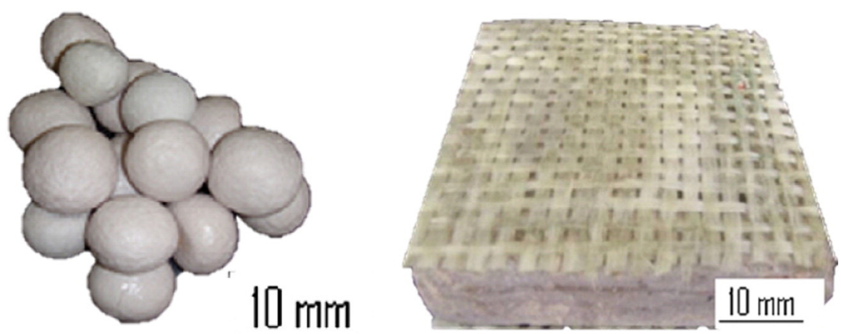

Fig. 16. Recycled glass foam particles (left); specimen tested in [88] (right).

advantages of using straw bale for thermal insulation purposes in buildings; measurement performed in an innovative sustainable house, built in Lithuania, showed that this material contributes to reduce heating degree-days by about 52% and to obtain a 1917 kWh solar gain during the heating season [86]. Dance et al. compared the sound insulation properties of several plastered straw bale walls with and without a double layered plasterboard partition with all European requirements for dividing walls. The results showed that only the addition of the plasterboard partitions made the sound insulation properties of the tested sample compliant to all national requirements. The results of the sound insulation tests performed on the 450 mm straw bale walls in terms of standardized airborne façade sound insulation are reported in Fig. 15 [87]. The average wheat world production in the period 1993–2013 is 6.14×10^{11} kg, mainly produced in Asia (43.6%) and in Europe (32.1%) [48].

3.2. Recycled materials

Recycling synthetic materials or using industrial by-products can be a sustainable strategy to reduce the use of virgin material and the disposal in landfill. As a consequence several researches were carried out to find innovative and sustainable uses for this category of materials, also in the building sector: the present section reports the results of the most interesting studies in this field.

3.2.1. Recycled glass foam and fibers

Several studies proved that glass wastes can be successfully recycled for the realization of thermal and acoustic insulation materials using foaming processes. Ayadi et al. realized a 450 kg/m^3 dense material characterized by a very low thermal conductivity, 0.031 W/mK. The tested specimen was a sandwich material in which the foam was placed between two layers of glass fibers (Fig. 16) [88]. Some products using recycled glass fibers are currently commercialized: the thermal conductivity is between 0.038 and 0.050 W/mK and the density between 100 and 165 kg/m^3 [89,112].

3.2.2. Recycled plastics

Polyethylene terephthalate (PET) is one of the most produced plastic materials, used in particular in the packaging and bottle production industry. Finding new strategies to recycle this material allows to reduce oil consumption and, above all, to contain environmental impacts due to inadequate disposal operations. PET bottles (75%) and virgin thermobonding PET (25%) were used to produce innovative insulation panels in [90]. The panel was characterized by a low thermal conductivity, 0.0355 W/mK, considering a 30 kg/m^3 dense material. The LCA analysis showed that the energy consumption and the global warming

Fig. 17. Samples made of recycled PET tested in [93].

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Table 1
Thermal and sound absorption properties of sample tested in [93] containing recycled PET. RPET was the mat containing only recycled mat. CWP and DWP were made with the 50% respectively of Coring and Dorper wool.

Sample code	Average thermal conductivity [W/mK]	Average sound absorption coefficient			
		50–1000 Hz	1000–2000 Hz	2000–5700 Hz	50–5700 Hz
RPET	0.035	0.09	0.34	0.81	0.61
CWP	0.032	0.13	0.48	0.89	0.71
DWP	0.033	0.18	0.58	0.95	0.75

Fig. 18. Panel made of recycled cotton (left) and denim (right) [94,95].

potential per functional unit was respectively of 83.723 MJ_{eq} and 1.783 kg CO_{2eq}. These data were obtained considering the functional unit as the quantity of material able to achieve a thermal resistance of 1 m^2K/W with a 1 m^2 panel. A similar study [91] reported the environmental performance of a commercial material characterized by a value of thermal conductivity of 0.036 W/mK. Similar values were obtained for commercial PET-based products [92]; moreover the panels were characterized by high values of the absorption coefficient, higher than 0.6 for frequencies above 500 Hz considering at least 30 mm of material. Recently, a study demonstrated that the addition of waste sheep wool to PET fiber reduces thermal conductivity from 0.035 to 0.032 W/mK and it increases sound absorption coefficient from 0.61 to 0.75 (average value between 50 and 5700 Hz) (Fig. 17, Table 1) [93]. An interesting method to recycle PET, HDPE (High Density Polyethylene) and PVC (Polyvinyl chloride) wastes for thermal insulation purposes in extremely poor high altitude areas is reported in [96]: the authors present an activity performed in Nepal where they proposed to collect clean plastic wastes into bags and place these bags inside cavity walls or also on ceilings. This technique allows to better insulate building and contemporary to reduce the quantity of material disposed in landfill, particularly problematic in these areas. A study performed by the Authors reported the thermal and acoustic effect of mixing exhaust sheaths of electric wires with concrete to improve the performance of screeds. The measured thermal conductivity was 0.189 W/mK, lower than 0.800 W/mK of common lightweight screeds. Concerning the damping properties, an impact sound pressure reduction of 17 dB was observed [97,98]. The presence of several footwear industries in northeast Brazil encourages the development of innovative use for these production residues. For instance Melo et al. studied the thermal performances of a gypsum board made with an ethylene-vinyl acetate material derived from the cuttings of expanded sheets in the shoe industry. The measured thermal conductivity was of 0.26 W/mK [99]. Finally, the substitution in mortars of part of the siliceous sand with recycled plastic (polyolefin and PET) allows to reduce their thermal conductivity, but also the compressive strength [100].

3.2.3. Recycled cotton and denim

Several manufacturers produce thermal and sound insulation materials using recycled cotton fibers (Fig. 18). The thermal conductivity of these products are between 0.039 and 0.044 W/mK while their density is quite low (25–45 kg/m^3). The densest and best thermal conductive materials have also the best acoustic absorption properties and are characterized by a specific heat of 1.6 kJ/kg K [94]. Similar values are declared by a manufacturer of special bats made of recycled denim characterized by high values of the sound absorption coefficient [95] (higher than 0.95 at 125 Hz for a thickness of 89 mm tested in accordance with [38]).

3.2.4. Recycled textile fibers

Manufacturing of textile products causes a large quantity of wastes, commonly disposed into landfill or used for energy recovering. In the European Union new strategies for the recovery of textile wastes are urgently needed, since only 1.5 of 5.8 Mton are currently recycled [101]. Valverde et al. realized a material made from synthetic textile industry scraps, constituted of polyester and polyurethane. The thermal conductivity of the tested samples was between 0.041 and 0.053 W/mK (Fig. 19). The lowest value was measured for the sample characterized by a density of 396 kg/m^3 [102]. The thermal insulation properties of materials realized using two different kinds of acrylic textile wastes were presented in [103]. The best performing material was characterized by a thermal conductivity of 0.044 W/mK and a density of 440 kg/m^3. Innovative insulation panels constituted by two external layers (2.5 mm thick) of polyethylene fibers and an internal one of ground waste

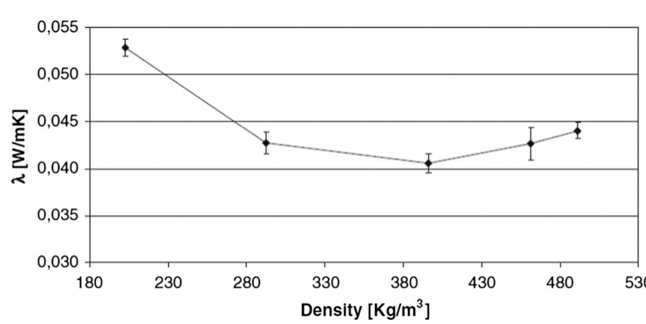

Fig. 19. Thermal conductivity values of specimens made of recycled textile fibers, characterized by different densities, tested in [102].

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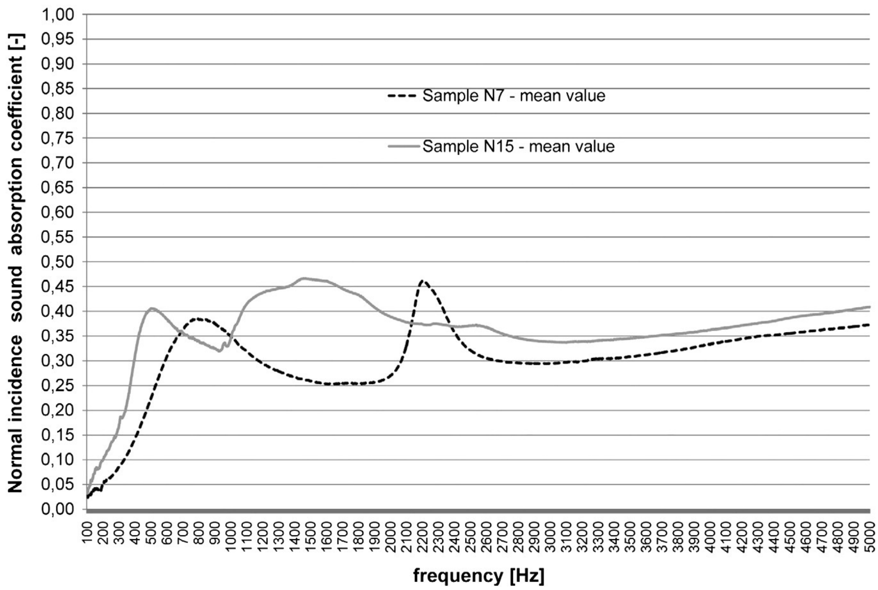

Fig. 20. Sound absorption coefficient of samples made of polyethylene fibers and waste paper tested in [104].

paper bonded with synthetic glue were tested in terms of thermal, acoustical and environmental properties in [104]. Two samples were analyzed, N7 and N15, different only for the thickness of the middle layer (respectively of 7 and 15 mm). The thermal conductivity of the tested samples was of 0.034 for N7 and of 0.039 W/mK for N15. Thermal conductivity was measured using the Hot Box method. Sound absorption coefficient, measured with the impedance tube, is reported in Fig. 20. Some manufacturers working in the building sector have already understood the potential of recycled textile materials and they are using them to produce thermal insulation panels and resilient mats for floating floors. The most performing thermal insulation product shows a thermal conductivity of 0.0358 W/mK, a water vapor resistance of 2.2 and a density of 80 kg/m^3. The same product is characterized by a sound absorption coefficient higher than 0.85 for frequencies above 500 Hz. As far as the damping properties, the dynamic stiffness value of 41 MN/m^3 was measured for a 3.5–4.5 mm thick sample [92]. Some commercialized materials made of recycled textile fibers reach a specific heat value of 1600 J/kgK [113, 114].

3.2.5. Others

Van de Lindt et al. proposed to recycle fly ash residue from energy plants to produce a thermal insulation material. The material was made of 65% fly ash, 26% water and 9% scrap tire fibers; the thermal conductivity of the sample was 0.035 W/mK. It is worth noting that the study was performed in the USA, where about 55% of fly ash is stocked in landfill. Issues related to the release of dangerous chemical compounds from this kind of material were not analyzed [105]. Sherely et al. used local banana and polypropylene fibers to produce an innovative composite material [106]. The effects of varying the quantity of the two components and of different chemical and physical treatments were analyzed. The most performing sample had a thermal conductivity of 0.157 W/mK, a density of about 980 kg/m^3 and a thermal diffusivity of $1.05 * 10^{-7}$ m^2/s. A similar study reporting the performance of a composite made of waste grass broom fiber and a polyester resin showed that the higher the percentage of natural fiber the lower the thermal conductivity. Nevertheless samples with lower concentrations of synthetic binder have also the highest values of thermal diffusivity. The lowest measured value of thermal conductivity was 0.196 W/mK [107]. Two other nature fiber based composite materials were analyzed in [108]. The first one was a composite of polyester, banana and sisal fibers, while in the other one polyester was used with pineapple leaves and glass fibers. As stated in [106,107], adding natural fibers causes a decrease of the thermal conductivity of the material; the lowest measured value was 0.140 W/mK. It is worth noting that the materials studied in [106–108] are structural materials and not thermal insulators.

4. Comparative analysis of the thermal performance of unconventional insulation materials

Tables 3 and 4 summarize the thermal properties of the materials investigated in the present paper. Colors were used to highlight the performance in terms of thermal conductivity. Red color indicates materials characterized by poor performance, with $\lambda > 0.08$ W/mK. Green color is used for the best material having $\lambda < 0.05$ W/mK, while yellow is used for the remaining ones, characterized by an intermediate performance. The specific heat was measured only in a few studies both for natural and recycled products, while density and thermal conductivity values are available for all materials. Concerning natural materials (Table 3), the lowest thermal conductivity value (0.035 W/mK) was measured in samples made of pineapple leaves having a density of 210 kg/m^3. The specimens made of straw bale are characterized by thermal conductivity values comparable to commercialized products, but their low values of specific heat and density negatively affect thermal diffusivity. Thermal insulation materials made of reeds seem to be characterized by the best thermal insulation performance but the studies about this kind of materials should be deepened, especially concerning diffusivity. A detailed comparison between thermal insulation performance of natural unconventional materials and the conventional ones (a non-exhaustive list is reported in Table 2) cannot be defined because of the lack of data about specific heat (reported only for banana and PP fiber, cotton, reeds, sansevieria fiber and straw bale). Reed-based materials are characterized by density and specific heat similar to rock wool but have also a higher thermal conductivity value. The thermal insulation materials made of recycled cotton have density and thermal conductivity values similar to the ones of EPS, XPS and sheep wool (Table 2) and also a high specific heat value (1.6 kJ/kgK). Further investigations should be carried out on sample made of pineapple leaf fibers since its thermal conductivity is low and its density is high; if this material is characterized by a value of specific heat higher than 1 kJ/kgK, its thermal performance could be compared to that of rock wool. Insulators made of residues of sugar cane (bagasse) and rice production are interesting thanks to their huge availability and low cost even if their thermal performance is not high as the one of pineapple leaves or cotton-based samples.

Table 2
Summary of thermal properties, fire classification and μ-value of some conventional insulation materials.

	Density (kg/m^3)	Thermal conductivity (W/mK)	Specific heat (kJ/kgK)	Fire classification	Water vapor diffusion resistance factor, μ–value
Rock wool	40–200	0.033–0.040	0.8–1.0	A1–A2	1.0–1.3
Expanded Polystyrene (EPS)	15–35	0.031–0.038	1.25	E	20–70
Extruded Polystyrene (XPS)	32–40	0.032–0.037	1.45–1.7	E	80–150
Kenaf	30–180	0.034–0.043	1.6–1.7	B2	1.2–2.3
Sheep wool	10–25	0.038–0.054	1.3–1.7	B1–B2	1.0–3.0

Products made of recycled-materials are characterized by better thermal insulation performance compared to the natural ones (Table 4). In particular, the one made of recycled glass has a density, thermal conductivity and specific heat values similar to rock wool (Table 2). Recycled textile materials are characterized by low thermal conductivity but also by low density; their insulation performance can be compared to the ones of lightweight synthetic materials such as expanded polystyrene (EPS) and extruded polystyrene (XPS). The specimen made of recycled

Table 3
Summary of thermal properties, fire classification and μ-value of natural unconventional insulation materials. Colors indicate qualitatively the thermal insulation performance (green = good, yellow = intermediate, red = poor). NA: not available.

Natural materials	Density (kg/m^3)	Thermal conductivity (W/mK)	Specific heat (kJ/kgK)	Fire classification	Water vapor diffusion resistance factor, μ–value	References
Banana and polypropylene (PP) fiber	980–1040	0.157–0.182	1.3–1.5	NA	NA	[106]
Bagasse	70–350	0.046–0.055	NA	NA	NA	[55], [56], [57]
Corn cob	171–334	0.101	NA	NA	NA	[64], [65]
Cotton (stalks)	150–450	0.0585–0.0815	NA	NA	NA	[66]
Date palm	187–389	0.072–0.085	NA	NA	NA	[67], [68]
Durian	357–907	0.064–0.185	NA	NA	NA	[69]
Oil palm	20–120	0.055–0.091	NA	NA	NA	[56]
Pecan	600–680	0.0884–0.1030	NA	NA	NA	[76]
Pineapple leaves	178–232	0.035–0.042	NA	NA	NA	[74]
Reeds	130–190	0.045–0.056	1.2	E	1–2	[109], [110], [53], [111]
Rice	154–168	0.0464–0.566	NA	NA	NA	[76]
Sansevieria fiber	1410	0.132	1.52	NA	NA	[79]
Sunflower (cake from biorefinery)	500–585	0.0885–0.110	NA	NA	NA	[81]
Sunflower (pitch)	36–152	0.0385–0.0501	NA	NA	NA	[80]
Straw bale	50–150	0.038–0.067	0.6	NA	NA	[83], [84], [85]

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Table 4
Summary of thermal properties, fire classification and μ-value of recycled unconventional insulation materials. (green = good, yellow = intermediate, red = poor). NA: not available.

Recycled materials	Density (kg/m^3)	Thermal conductivity (W/mK)	Specific heat (kJ/kgK)	Fire classification	Water vapor diffusion resistance factor, μ–value	References
Cotton (recycled)	25–45	0.039–0.044	1.6	E	1–2	[94]
Cotton (recycled denim)	NA	0.036–0.038	NA	NA	NA	[95]
Recycled glass	450	0.031	0.83	NA (probabily A1)	NA	[88]
Recycled glass (commercialized)	100–165	0.038–0.05	1.0	A1	Very high	[89], [112]
Recycled PET	30	0.0355	NA	NA	NA	[90]
Recycled PET (commercialized)	15–60	0.034–0.039	1.2	B	3.1	[92]
Recycled textile (commercialized)	30–80	0.0358–0.042	1.2–1.6	E, F	2.2	[92], [113], [114], [115]
Recycled textile fibers (polyester and polyurethane)	440	0.044	NA	NA	NA	[103]
Recycled textile fibers (synthetic)	200–500	0.041–0.053	NA	NA	NA	[102]
Recycled textile and paper	433	0.034–0.039	NA	NA	NA	[104]

textile and paper [104] is characterized by low thermal conductivity values and by a high density, but unfortunately the specific heat was not measured.

5. Comparative analysis of reaction to fire and water vapor resistance factor

Tables 2, 3 and 4 report also the reaction to fire and the water vapor resistance factor of conventional and of natural and recycled unconventional insulators. Only 2 of the 16 natural unconventional materials are characterized in terms of reaction to fire class and water vapor resistance factor while more information are available about the recycled ones. Concerning the reaction to fire, the E performance of insulators made of recycled cotton is similar to the one obtained by kenaf and sheep wool based materials. The insulator made of recycled glass is classified with the non-combustible class A1, similar to rock wool. Insulators made of recycled cotton and reeds are characterized by a high permeability to vapor, similar to mineral and natural wool. The analyzed materials made of recycled glass acts as a vapor barrier. However there is a wide lack of data about these properties that are defined only for some of the unconventional materials yet commercialized. The research studies about thermal, acoustic and environmental properties of innovative insulators rarely investigate reaction to fire and water vapor resistance. These properties are not usually evaluated at an early stage, probably because they could be modified using additives or systems (i.e. vapor barrier).

6. Comparative analysis of the acoustic performance of unconventional insulation materials

The acoustic properties of the natural and recycled unconventional materials studied in the paper are reported respectively in Tables 5 and 6. A deeper analysis about these performances is reported in [47], while in these sections only a comparison between the products shown in the paper is summarized. The majority of the investigated materials are made of fibers or granules and can be considered as porous materials with interconnected cavities. These properties are required to obtain good sound absorption materials that can be used in enclosed spaces for reduce reverberation at medium-high frequencies or in air-spaces of double walls to increase sound insulation. Since acoustic properties depend on frequency, direct comparisons, as those made for thermal properties, cannot be easily performed. Moreover sound insulation of a double wall depends on all its elements and not only on the insulation material. Nevertheless some interesting results can be presented. Concerning the performance of reeds, the results of the studies described in [49–51] are not completely comparable since different methods were used. The outcomes of the different researches demonstrated the promising acoustic absorption performance of these kinds of materials. The commercialized products made of recycled textile and denim are characterized by values of acoustic absorption, expressed by NRC, close to 1. Concerning sound insulation issues, Tables 5 and 6 report only the weighted sound reduction indexes R_w of two similar double walls. R_w greater than the ones indicated in Table 6 were measured considering a thicker double wall. It should be observed that the minimum value of R_w for multi-story buildings in Europe is comprised between 50 dB and 55 dB. Tests carried out in field and in laboratory on different plastered straw bale walls proved that these systems do not meet the majority of European sound insulation requirements [87].

7. Comparative analysis of the LCA performance of thermal insulation materials

The results of LCA analyses of the examined unconventional thermal insulation materials are summarized in Table 7, together with data related to other common insulation materials such as extruded and expanded polystyrene, kenaf, rock and sheep wool. Embodied energy and global warming potential of these products are reported respectively in Figs. 21 and 22. Since these materials are only at a prototypal stage or at an early stage of commercialization, few information about their

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Table 5
Summary of acoustic properties of natural unconventional materials.

Natural materials	Thickness (mm)	Acoustic absorption	Acoustic absorption: method	Acoustic insulation	Acoustic insulation: method	Reference
Reeds	4.9–74.2	$SAA_{200-1250} = 0.08–0.54$	Impedance tube	NA	NA	[49]
Reeds	NA	α > 0.5 for f > 300 Hz	Impedance tube	NA	NA	[50]
Reeds	140	α > 0.4 for f > 160 Hz α ≈ 1 for f > 315 Hz	Reverberation room	NA	NA	[51]
Straw bale	450 (wall)	NA	NA	$D_{nT} \approx 30$ dB for f = 125 Hz $D_{nT} \approx 70–75$ dB for f = 400 Hz	ISO 140-4: 1998	[87]

Table 6
Summary of acoustic properties of recycled unconventional materials.

Recycled materials	Thickness (mm)	Acoustic absorption	Acoustic absorption: method	Acoustic insulation	Acoustic insulation: method	Reference
Recycled denim (commercialized)	89	NRC = 1.15	Reverberation room	NA	NA	[90]
Recycled textile (commercialized)	50	NRC = 0.85	Reverberation room	$R_W = 52$ dB	1.5 cm plaster + 12 cm perforated brick + 1.5 plaster + 3 cm insulator + 2.5 cm plasterboard	[92]
Recycled textile (commercialized)	30–60	0.62	Reverberation room	$R_W = 53$ dB	1 cm plaster + 8 cm perforated brick + 1 cm plaster + 4 cm insulator + 2.5 cm plasterboard	[115]
Recycled textile and paper	7, 15 (between two 2.5 thick layers of polyethylene fibers)	NRC = 0.25, SAA = 0.29 (7 mm) NRC = 0.40, SAA = 0.38 (15 mm)	Impedance tube	NA	NA	[104]

environmental impact are currently available. Data reported in Table 7 are referred to a functional unit defined as the mass of material needed to obtain a thermal resistance of 1 m^2K/W; conversions were made if data were related to 1 kg of material. The methods used for the LCA analysis unfortunately were not the same, so in Table 7 the system boundary and the approach is specified. In particular some studies applied the cradle to gate approach (CTGA) while others the cradle to grave one (CTGR). The results of the comparative analysis showed the good environmental performance of the studied unconventional materials except for the one made of recycled textile and paper described in [73]. This material is characterized by high values of energy consumption (267.7 MJ/functional unit) and global warming potential (14.38 $kgCO_{2eq}$/functional unit), so the production processes should be revised. Recycled textile materials are characterized by an environmental performance similar to the ones of a sheep wool product as can be clearly seen in Figs. 21 and 22. It is worth noting that the material made of recycled PET studied in [90] is characterized by a lower GWP value compared to the one of the kenaf-based material, whereas the one made of recycled PET defined in [92] has also better performance in terms of embodied energy. These results were obtained despite the fact that this study considers also the disposal phase.

8. Conclusions

The present paper reports an up to date review of some building insulation products made of unconventional material. While the market is now dominated by few categories of thermo-acoustic insulators such as mineral wool, extruded and expanded polystyrene, the rush towards more environmentally friendly buildings outlines developing opportunities for new sustainable materials. Several researches investigated thermal, acoustic and environmental performance of materials at current scarcely used or even in a prototypal stage. These unconventional products can be manufactured using natural sources such as residues of agricultural production and processing industries. Other sources are represented by recycled products or industrial plants byproducts. Some of the investigated materials are characterized by performance similar to commercial ones. Concerning thermal issues, an example is given by a recycled cotton insulator having density and thermal conductivity comparable to EPS, XPS and sheep wool. As far as the acoustic performance, high sound absorption and insulation values were measured in materials made of recycled denim. Products made of recycled PET and textile are also characterized by environmental performance better than rock wool and kenaf fiber ones.

Table 7
Comparative analysis of the LCA of thermal insulation materials. CTGR stands for cradle to grave, CTGA stands for cradle to gate.

Material	Functional unit weight (kg)	Thermal conductivity (W/m^*K)	Energy consumption (MJ_{eq} per functional unit)	Global warming potential ($kgCO_{2eq}$ per functional unit)	Approach and System Boundary	Reference
Recycled PET	1.065	0.0355	83.723	1.783	CTGA, Italy	[90]
Recycled PET (commercialized)	1.48	0.037	21.056[a]	3.117	CTGR, NA	[92][b]
Recycled textile (commercialized)	1.79	0.0358	17.57[a]	1.545	CTGR, NA	[92][b]
Recycled textile and paper	14.7	0.034–0.039	267.7	14.68	CTGA, Italy	[104]
Extruded expanded polystyrene	1.75	0.035	127.31	13.22	CTGA, European	[116][a], [117][a]
Kenaf	1.52	0.038	59.37	3.17	CTGA, Italy (400 km)	[54]
Rock wool	1.2	0.04	53.09	2.77	CTGA, European	[116][a], [117][a]
Sheep wool	0.76	0.038	17.119	1.457	CTGR, NA	[92][b]

NA: not available.
[a] Information updated through SIMAPRO elaboration.
[b] Original data given referred to 1 kg of product and not to 1 functional unit. Moreover the use phase was not considered.

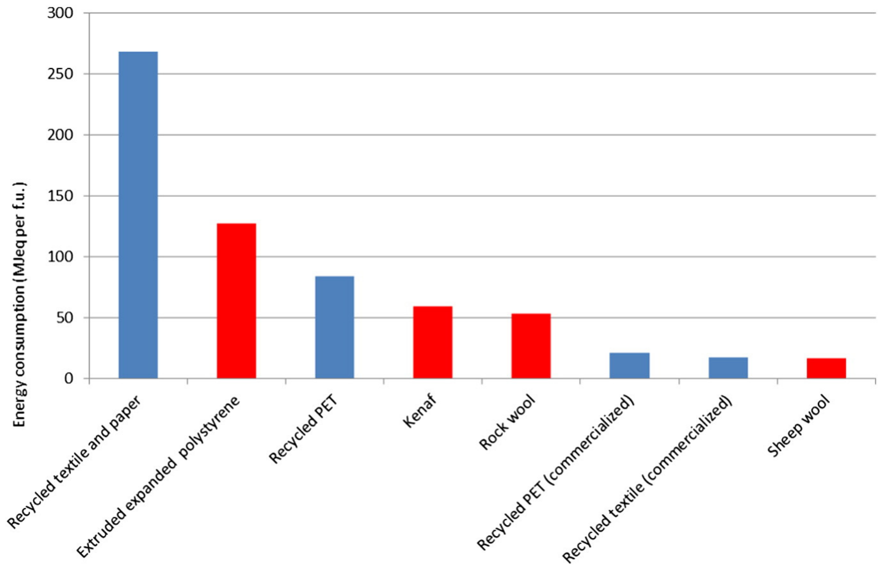

Fig. 21. Embodied energy, in terms of MJ_{eq} per functional unit, of thermal insulation materials. Unconventional materials are in blue, others in red.

However the majority of the investigated materials are not completely characterized. As far as thermal properties, thermal conductivity is always reported but data about specific heat is often missing. The latter data is crucial for the evaluation of thermal dynamic properties. Concerning sound absorption and insulation materials, reliable data are available only for a small number of products. Trusty comparisons can be made only between tests performed using the same procedure; for instance it should be noticed that sound insulation tests are usually carried out on double walls containing the insulators, but the overall performance is given by all its components. Concerning sound absorption, comparisons can hardly be made since the properties can be measured with different methodologies. Very few studies evaluate the environmental impacts in a rigorous way using for instance the LCA approach; this lack of data is mainly caused by the state of the research on these materials that is still at an early stage. Further analyses should be also performed to evaluate other important properties for building insulator such as fire classification and resistance to water vapor diffusion. These parameters are usually available only for commercial materials, whereas further studies are needed for unconventional ones. These properties can be enhanced using additives or using systems (i.e. a vapor barrier), but in this case an additional environmental impact is produced and it should be assessed.

In conclusion there are still issues that remain to be solved before a widespread use of unconventional materials. Some properties should be further investigated such as durability fire resistance, water vapor diffusion, fungal resistance in particular for the best performing materials. An important requirement influencing the sustainability of these insulators is related to the availability of its components since the use of local materials lead to a reduction of economic and environmental impacts. The production of insulators made of natural materials should not be in conflict with the plantation and harvesting of food crops, but it should be focused on using residues and byproducts of the agricultural sector. Using these unconventional materials can reduce the use of oil-based and not renewable sources; moreover residues of sugarcane, pineapple and rice are generated mainly in places where there is a huge necessity to reduce summer cooling consumptions.

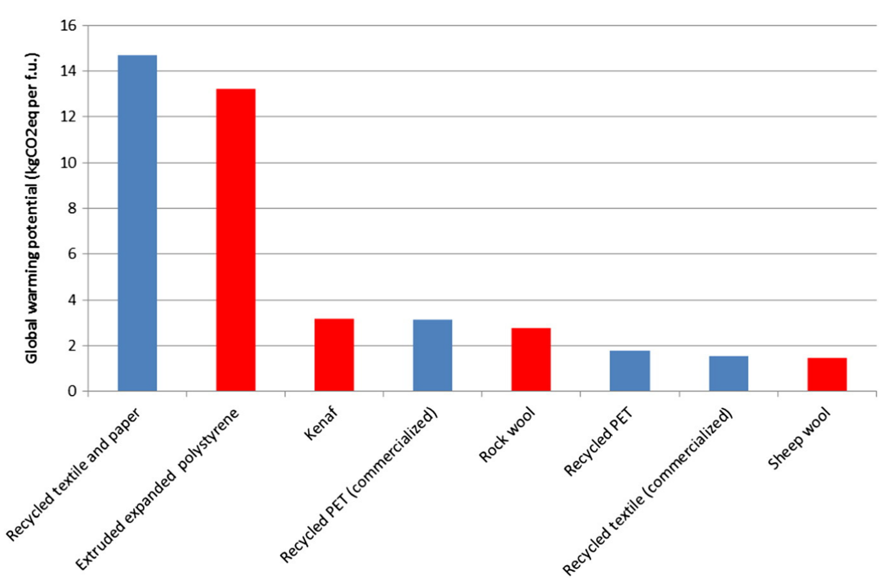

Fig. 22. Global warming potential, in terms of $kgCO_{2eq}$ per functional unit, of thermal insulation materials. Unconventional materials are in blue, others in red.

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