

A Review of Natural Bio-Based Insulation Materials

Livia Cosentino , Jorge Fernandes  and Ricardo Mateus * 

Institute for Sustainability and Innovation in Structural Engineering (ISISE), Associate Laboratory Advanced Production and Intelligent Systems (ARISE), Department of Civil Engineering, University of Minho, 4800-058 Guimarães, Portugal; ltcosentino@hotmail.com (L.C.); jepfernandes@rever.pt (J.F.)

* Correspondence: ricardomateus@civil.uminho.pt

Abstract: Within the context of climate change and the environmental impact of the building industry, insulation materials contribute to improving the thermal performance of buildings, thus reducing energy demand and carbon emissions during the operation phase. Although most of them are responsible for significant carbon emissions during their production, bio-based insulation materials can provide good performance with low carbon emissions. This paper aims to investigate natural insulation materials' properties and environmental impacts through a literature review. Due to the growing importance of Environmental Product Declarations (EPDs) on specification requirements, many manufacturers already disclose environmental data related to their products, allowing for a comparison between thermal insulation solutions. In academic research, embodied environmental impacts are not as explored as physical properties. In addition, from the analysis of results, it is possible to conclude that the characterization of the physical properties of this type of material is normally focused on thermal conductivity. Nevertheless, most studies overlook other important parameters of these materials, such as the thermal capacity, lifetime, and environmental impacts. This is something that is necessary to overcome in future developments to allow for a comprehensive comparison between the properties of different (conventional and bio-based) insulation materials.

Keywords: bio-based insulation; natural insulation material; building insulation; sustainable building



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1. Introduction

Climate change's consequences on the world are already well known, and the most recent publications show an increased urge to deal with the transition to a more sustainable way of life on the planet. According to the latest Intergovernmental Panel on Climate Change (IPCC) report [1], limiting global warming to 1.5 °C or even 2 °C is hardly possible without a significant reduction in greenhouse gas (GHG) emissions. Emissions should be reduced by 45% from 2010 levels before 2030 to limit temperature rises and not cause an irreversible impact [2].

On this topic, construction is a key sector in which to intervene. In Europe, for example, buildings are responsible for 40% of the energy used, 36% of energy-related GHG emissions, and 80% of household energy use is related to thermal comfort [3]. Furthermore, the built environment is responsible for 50% of all the materials extracted and 35% of all waste produced [4]. In G7 countries, GHG emissions from the residential building material cycle can be reduced by 80 to 100% by 2050, with the efficient use of materials and by using recyclable materials [5].

In the European context, some strategies to address decarbonization have been developed under the scope of the European Green Deal [6], which aims at Europe becoming the first climate-neutral continent by reducing greenhouse gas emissions by 55% by 2030. As a consequence, the Energy Performance Building Directive (EPBD) recast 2022 will have a deep impact on the future thermal regulations of member states [7]. The revision envisages double renovation rates in the next ten years as well as demanding the calculation of the life cycle Global Warming Potential (GWP) for new buildings from 2030 onwards. Not

only energy performance will be considered but also healthy indoor climate conditions, adaptation to climate change, and carbon storage in buildings, among others.

Therefore, it is necessary to develop methodologies to support adequate decision making in the choice of materials to promote energy efficiency since it can lead to a considerable reduction in life cycle energy use and GHG emissions. This reduction can be between 35% and 40% [5], and most of it can result from the use of renewable-based materials [8]. The new circular economy action plan [4] emphasizes the importance of recycled materials to reduce emissions in the production stage. This highlights the importance of using natural and recyclable materials, as synthetic materials have a more complex recycling process.

In this context, building insulation is crucial to reduce operational energy, especially to reduce heat losses. However, insulation materials are one of the largest contributors to emissions and, therefore, to the environmental impacts of the construction materials. Research on 503 buildings found that 26.1% of total carbon emissions came from insulation material production [9], the largest after concrete production that represents 33% [9]. Nonetheless, with recent concerns to improve energy efficiency, more insulation tends to be used in buildings. It is estimated that the global market of thermal insulation materials will continue to grow, and plastic-based foam insulations, such as Extruded Polystyrene (XPS) or Expanded Polystyrene (EPS), which already represented 41% of the insulation product market in 2015, will have the highest growth rate [10].

Embodied carbon in insulation products varies a lot, but there is a clear difference in solutions based on biological materials since they can have a carbon-negative balance [11].

Figure 1 shows a comparison between different insulation materials, considering a functional unit of 100 m² and a thermal resistance of 5 (m²K)/W. From the graphs, it is possible to verify that bio-based materials have the best GWP performance over plastic- and mineral-based solutions. However, despite carbon sequestration due to biogenic carbon, a thicker layer of the material might be needed to provide the same thermal resistance. A comparison between insulation material thickness and carbon dioxide emissions for a thermal resistance of 5 (m²K)/W can be observed, adapted from [9].

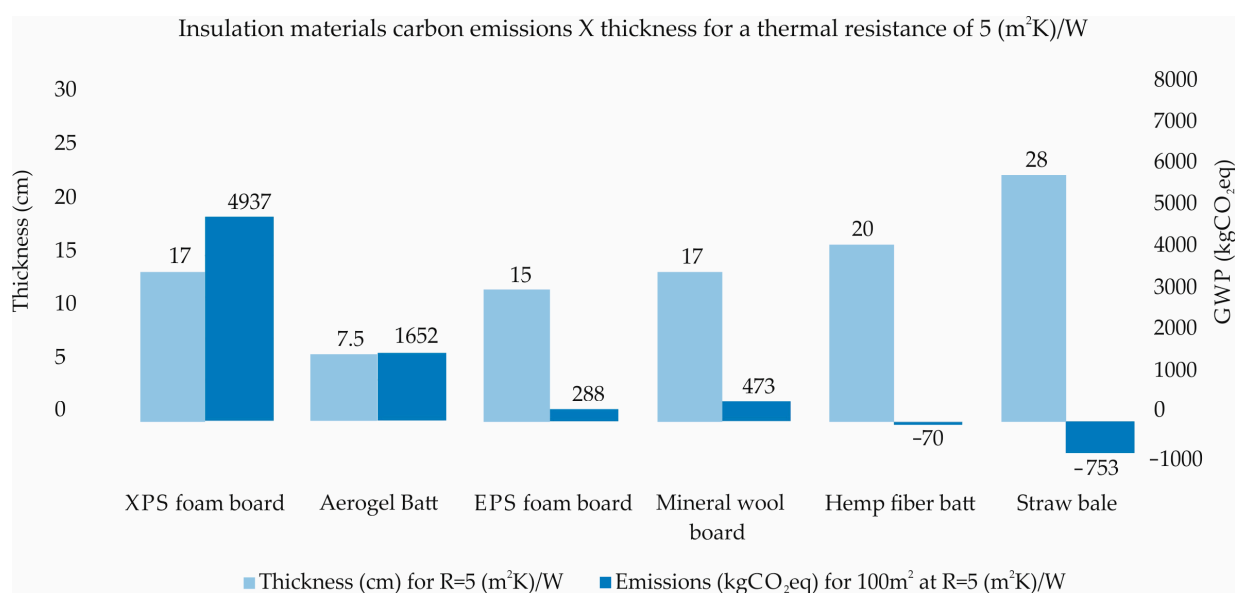


Figure 1. Comparison between insulation material thickness and carbon dioxide emissions for a thermal resistance of 5 (m²K)/W. Adapted from [9].

Thus, taking Figure 1 into consideration, it is essential to develop new insulation solutions that have low embodied environmental impacts and can fulfil the functional requirements for maximum comfort.

When it comes to building renovation, which is specially addressed in the latest European directive, EPBD recast 2022 [7], it is essential to understand that in the past, passive strategies, including the use of bio-based insulation materials, were the main principle to deal with thermal comfort. For example, some vernacular timber buildings on Portugal's coastline used an external cavity wall filled with reed to provide thermal insulation [12]. All over the world, natural fibers have been used in thatched roofs, as well as in woven walls made of weeds or bamboo covered by clay plasters [13]. In the Baltic Sea region, a common reed (*Phragmites australis*) was used as an insulation layer outside of a log wall due to its good thermal insulation capacity and water vapor permeability [14].

In energy renovation, although external insulation is the best solution, in some cases, internal insulation is the only option. In both scenarios, natural materials should be chosen to comply with functional requirements and technical features of the existing structure/support [15]. In some construction systems, such as natural-based ones (e.g., earthen walls, timber, etc.), conventional thermal insulation materials can create or aggravate possible anomalies, mainly due to their low vapor permeability [16].

In this sense, due to the potential of bio-based thermal insulation solutions to improve both the thermal and environmental performance of buildings, this study aims to investigate and compare the functional and environmental characteristics of bio-based materials through an extensive literature review. The research focuses on organic bio-based-derived and innovative materials, which can improve the thermal comfort of buildings at a lower potential environmental impact, both for renovation and in new constructions.

2. Materials and Methods

In this section, a detailed description of the methodology used is presented. The systematic literature review followed the framework presented in Figure 2.

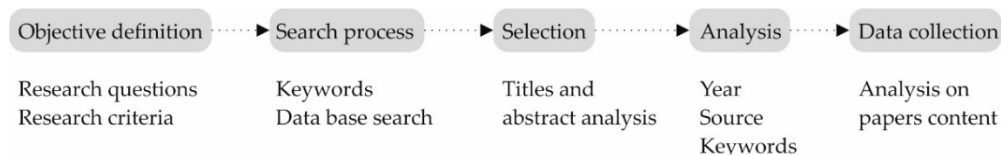


Figure 2. Methodology's framework.

The research questions that guided this work are:

- Are bio-based materials suitable for building insulation?
- What are the main properties to consider in an insulating material?
- What is the environmental impact of bio-based insulation materials versus conventional insulation materials?

The research method was based on a review through a bibliometric approach to identify trends in natural insulation materials and their environmental impact.

The literature review was carried out through the Scopus database due to its representativity among academic works. Since this review focuses on the effectiveness of natural insulation materials, both from functional and environmental perspectives, four categories of keywords were selected for the search: natural building materials, thermal efficiency, carbon footprint, and some known natural materials.

The following keywords were used: "insulation"; "insulated"; "natural insulation"; "thermal insulation"; "insulated wall"; "thermal conductivity"; "thermal behavior"; "innovative bio-based panels"; "climate-neutral construction"; "natural construction"; "biocconstruction"; "green building"; "energy efficiency"; "thermal efficiency"; "thermal characterization"; "thermal performance"; "emissions"; "embodied carbon"; "carbon storage"; "biogenic carbon"; "carbon footprint"; "environmental impact"; and, "life cycle assessment"; "reed"; "hemp"; "straw"; "wool"; and "natural fiber".

Exclusion criteria were applied to language (only publications in English were selected), publication type (only journal articles and conference proceedings), and year of

publication (only the last 5 years' publications were considered, meaning 2022, 2021, 2020, 2019, and 2018).

The "Transparent Report Meta-Analyses (PRISMA)" [17] checklist was followed according to its four steps. In the identification step, 1243 results were found considering different keyword combinations. For the next step, called the screening stage, duplications were excluded, and 1179 results remained. In the third step, the eligibility check was conducted, and 81 publications were selected. The eligibility check step excluded publications about other ecological materials that are not for building insulation purposes or not related to the construction industry. In the fourth step of PRISMA, the inclusion step, the record continued to include the same 81 publications (Table 1).

The table below represents the keyword combinations made and the results found.

Table 1. Database search and results.

Keywords Combinations	Number of Publications Found	Number of Publications Found after Exclusion Criteria Applied	Number of Publications Found after Title and Abstract Analysis
"thermal conductivity" AND "green building" AND "insulation"	59	31	13
"thermal conductivity" AND {"green building" OR "natural construction"} AND {"insulation" OR "insulated" OR "insulated wall"}	64	34	11
{"thermal conductivity" OR "thermal resistance"} AND {"green building" OR "natural construction" OR "bioconstruction" OR "climate-neutral construction"} AND {"insulation" OR "insulated" OR "insulated wall"} AND {"thermal behavior" OR "energy efficiency" OR "thermal efficiency" OR "thermal performance"}	25	14	3
{"Emissions" OR "embodied carbon" OR "carbon storage" OR "biogenic carbon" OR "carbon footprint" OR "environmental impact"} AND {"thermal behavior" OR "energy efficiency" OR "thermal efficiency" OR "thermal performance"} AND {"climate-neutral construction" OR "bioconstruction" OR "natural construction" OR "green building"} AND {"insulation"}	46	15	6
{"innovative bio-based panel" OR "reed" OR "hemp" OR "straw" OR "wool" OR "natural fiber"} AND {"thermal behavior" OR "energy efficiency" OR "thermal efficiency" OR "thermal performance"}	2240	942	64
Total of publications without repetition		1179	81

Most of the publications are from Europe (54%) and Asia (25%); surprisingly, very few American and no Oceanic academic publications were found among the selected publications. The year with the largest number of publications was 2022, followed by 2021, showing a crescent interest in the field. The Journal *Construction and Building Materials* was the source responsible for 10% of them. The publications had a total of 839 citations on Scopus, 28% in 2021, 25% in 2019, and 24% in 2020. Figure 3 shows an overview of the publications selected to visualize the research context.



Figure 3. Publication's overview. (a) Year of publications, (b) research group's location, (c) source of publications, (d) number of citations per year.

To complement and allow for comparison, information with commercially available insulation products and environmental product declarations (EPDs) from different databases was also reviewed.

Three sets of parameters were reviewed and analyzed, as presented in the following sections: physical parameters, mechanical parameters, and environmental parameters.

2.1. Physical Parameters

Insulation materials are usually first classified by their physical properties. Density has a great influence on all other parameters, as further explained, and, therefore, it is an essential feature. The density unit commonly used is kg/m^3 and is defined by the material's mass per unit of volume, as presented in Equation (1):

$$\rho = m/V, \quad (1)$$

where ρ is the density, m is the mass, and V is the volume of the sample.

Bulk density can also define the number of voids present on a sample and whether the material is compacted or loose, which influences other characteristics.

Thermal conductivity is probably the most important feature of insulation materials, as it stands by the capacity to conduct heat and, therefore, to insulate. It is denoted by the

letter “ κ ” or “ λ ” and its SI unit is W/mK (Watts per meter Kelvin). Thermal conductivity measurement will depend on the heat flux through a material and is defined by Fourier’s law, in which its differential form is expressed in Equation (2):

$$q = -k \times \Delta t, \quad (2)$$

where q is the heat flux density in W/m² (Watts per square meter), κ is the thermal conductivity, and Δt is the temperature gradient expressed in Kelvin per meter. The lower the thermal conductivity, the better the insulation property of the material.

The standard ISO 9869-1 [18] is one of the standards most used to define thermal insulation of building elements. It defines the thermal resistance and the thermal conductance of a material or solution. Equations (3) and (4) represent calculations according to the ISO:

$$R = (T_{si} - T_{se})/q, \quad (3)$$

$$U = q/(T_i - T_e), \quad (4)$$

where R is the thermal resistance, q is the heat flux density, T_{si} and T_{se} stand for the temperature of the internal surface and temperature of the external surface, respectively, U is the thermal transmittance, and T_i and T_e are internal temperature and external temperature, respectively.

R -value and U -value depend on the thickness of the material or construction solution. Usually, researchers address these properties when comparing building solutions.

When talking about the thermal properties of insulation materials, it is essential to also explore the heat capacity of each material as well as diffusivity and effusivity properties. Once thermal conductivity is a measurement at a steady state, it is important to know how long it takes to achieve that state. That is the reason why heat capacity becomes an essential feature.

The higher the heat capacity, the smaller the thermal diffusivity, meaning that the heat will move more slowly through the material. Additionally, a greater thermal capacity will result in greater thermal effusivity, which means that the material will be cool to touch.

Thermal effusivity and thermal diffusivity are linked to the thermal conductivity, heat capacity, and density of a material. Equations (5) and (6) represent how effusivity (β) and diffusivity (α) are calculated, respectively:

$$\beta = \sqrt{\rho C_p k}, \quad (5)$$

$$\alpha = k/(C_p \rho), \quad (6)$$

where k is thermal conductivity; C_p is the specific heat capacity; and ρ is the density.

Another point of attention in evaluating thermal performance is thermal stability, which, according to standard ASTM E2550 [19], is the temperature at which the material starts to decompose or react. Thermal stability can be measured using a thermogravimetric analyzer (TGA) and defines the ability of the material to maintain its properties under extreme temperatures.

Beyond thermal properties, but also within the physical parameters, water absorption is a crucial property to provide durability to the material and avoid building pathologies. The water absorption coefficient, also known as sorptivity, is the moisture transport into the material. According to the standard ISO 62 [20], the water absorption coefficient is expressed using Equation (7):

$$c = \left(\frac{m_2 - m_1}{m_1} \right) \times 100\%, \quad (7)$$

where c is the change in mass; m_2 is the mass of the material after water immersion; and m_1 is the mass of the material after drying and before immersion.

Another related property is the water vapor diffusion resistance factor, the μ -value. This factor is the ratio of the water vapor permeability of the air and the material's water vapor permeability, which stands for the water vapor transmission rate through a certain area of the material at a unit thickness.

The last analyzed physical property is fire resistance, addressed in the standard EN ISO 13501-01 [21]. Fire resistance classification in Europe varies from A to F and will determine whether the insulation material can help stop the fire or collaborate to spread it in the building. Through the standard, it is also possible to classify the material in terms of smoke production and flaming droplets and particles.

2.2. Mechanical Parameters

In addition to physical parameters, mechanical characteristics should be analyzed on insulation materials to evaluate durability and application methods. Five properties are usually assessed on insulation materials, such as: compressive strength, flexural strength, tensile strength, modulus of rupture, and modulus of elasticity.

Compressive strength measurement is useful to assess the behavior of fragile materials and the relationship between linear deformation as a function of the applied load.

The flexural strength test evaluates how the material reacts in an elastic regime; it is also useful to determine the modulus of rupture (MOR). Tensile strength assesses the material deformation while a stretching effort is made; it will also define the modulus of elasticity (MOE) of the material.

Compressive, flexural, and tensile strengths and modulus of elasticity and rupture are measured in megapascals (MPa) or Newton per square millimeters (N/mm²).

2.3. Environmental Parameters

Considering the environmental issues discussed in the Introduction, beyond physical and mechanical parameters, it is essential to evaluate environmental parameters as well.

Considering a life cycle approach for the environmental assessment of buildings [22], this review considers the product stage only, from modules A1 to A3, as it is the minimum that must be considered in EPDs.

Under this stage, from raw material supply to manufacturing, including transport, three main parameters are analyzed: use of primary energy, considering renewable and non-renewable energy (measured in MJ), global warming potential (measured in kgCO₂ eq.), and, when applicable, biogenic carbon.

3. Results and Discussion

3.1. Sample Characterisation

Among the selected academic publications, 33 different materials were addressed. The most studied material was straw, followed by sheep wool, as shown in Figure 4. The analysis of academic research suggests a tendency to focus on plant fibers, especially agricultural waste and fast-growing plants.

Most publications addressed composite materials (77%, or 37 publications), while only 23% (11) focused on the raw material as a product. Among composite materials, 51% (19) used some chemical material, such as polypropylene composites, magnesium phosphate cement, or polyvinyl alcohol, mostly with a binder purpose. However, 49% (18) of total publications do not use any kind of artificial additive.

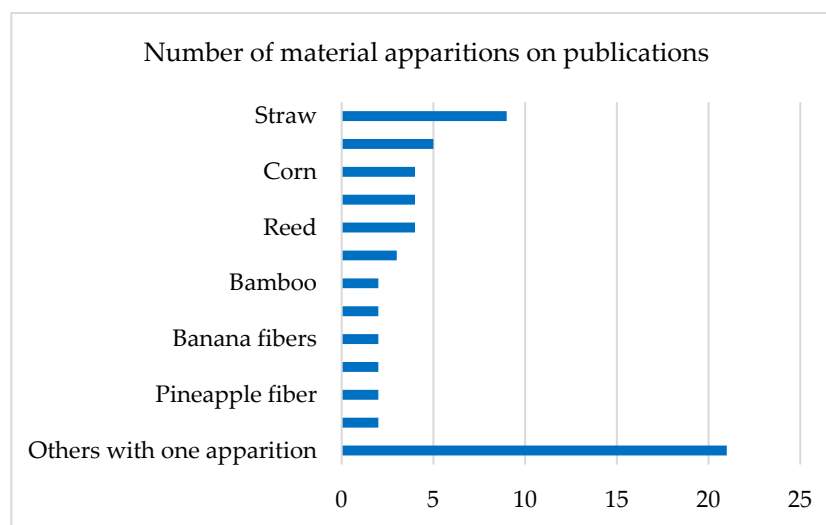


Figure 4. Number of occurrences in publications by type of material.

3.2. Physical Parameter Analysis

As previously cited, the following physical properties were analyzed: density; thermal conductivity; heat capacity; thermal effusivity; thermal diffusivity; thermal stability; water absorption and/or vapor permeability; and fire resistance. The physical properties of materials were the most cited parameters, especially density and thermal conductivity.

3.2.1. Density and Thermal Conductivity

Regarding thermal conductivity, several measurement methods have been used between steady-state and transient methods. No method preferences were observed, and no relationship was established between the values obtained and the measurement methods.

The most cited material in academic research, straw, presents great potential as an insulating material, which explains its importance in the research field. The lowest thermal conductivity for a wheat straw insulation panel, with a 4 cm length straw, was 0.046 W/mK for a density of 105 to 112 kg/m³ [23].

Changes in the way the material is used in the product can change its characteristics. By changing the orientation of fibers on a straw bale, with heat flow perpendicular to straw orientation, it is possible to improve thermal resistance and, therefore, reduce the thickness of the insulation product by 28% [24].

The second most cited material in the literature was sheep wool, a known commercial material with high insulation potential. Sheep wool's best values rely on the raw material characteristics, having a thermal conductivity of 0.0318 for a density of 30 kg/m³ [25]. Due to its insulation properties, some studies used wool as an aggregate to improve the thermal and/or mechanical performances of other materials, such as gypsum board [26] and brick [27].

Reed, as cited before, was a material used in vernacular buildings to improve thermal comfort, and research shows that its thermal conductivity can reach 0.056 W/mK for a density of 137 kg/m³ [28]. For a specific species known as giant reed (*Arundo donax*) and highly spread in Europe due to its invasive characteristics, the thermal conductivity is 0.063 W/mK for a density of 510 kg/m³ [29].

On the other hand, cork has a consolidated path in the construction industry. Its lower thermal conductivity is 0.044 W/mK for an agglomerated cork panel [30]. Other materials did not show such great thermal performance, except when used as aggregates for inorganic materials, such as cement.

Wood fiber insulation board has a thermal conductivity of 0.035 W/mK for a 100–150 kg/m³ density [31], similar to sheep wool [25]. Nevertheless, this value is obtained when the wood fiberboard is prepared with melamine formaldehyde-urea (MFU)

resin adhesive [31], which, theoretically, would increase the embodied potential environmental impact of this insulation product. Without chemical binders, wood insulation thermal conductivity values could increase to 0.048–0.055 W/mK [32], still presenting a good performance.

The banana–polystyrene composite presented a thermal conductivity of 0.0183 W/mK [33]. In addition, an aerogel composite of pineapple leaves and cotton waste showed good thermal performance and simultaneously a very low density [34]. These data reveal a great potential of plant fibers, namely of some types of leaves.

Hemp products showed similar values to those of tree bark [35,36] and have a thermal conductivity of around 0.05 W/mK [37]. However, hemp-based insulation has the disadvantage of high water absorption capacity, as values above 20% can double the thermal conductivity, and water absorption can lead to a 198% increase in mass and 40% in volume [37].

In the case of husk-based materials, their performance seems to depend on the origin of the species. Corn husk presented a thermal conductivity of 0.047 W/mK [23], whereas a composite with rice husk shows a value of 0.08 W/mK [38], and wheat husk presented a thermal conductivity of 0.1 W/mK [38].

In addition to the intention of creating insulation materials, many research works still show low thermal performances, meaning high thermal conductivity (TC) values for an insulation product, as for mussel shell (TC of 0.12 W/mK) [39], groundnut shell (TC of 0.27 W/mK) [40], or wine waste composite (TC of 0.35 W/mK) [41].

Concerning natural materials and their heterogeneity, most authors confirmed a wide range of values for thermal conductivity depending on various aspects, such as density [35,42] or particle size [39].

Lifang Liu et al. [43] showed that on a bio-insulation material based on wheat straw, the bigger the straw length, the lower the thermal conductivity and the lower the density of the sample. Further, for the Sabai grass polypropylene composite, the higher the density, the higher the thermal conductivity of the sample [44]. The same happened for wood fiber insulation boards [31]. It shows that there is a direct relation between density and thermal conductivity. Figure 5 shows this trend by presenting the relationship between the density and thermal conductivity.

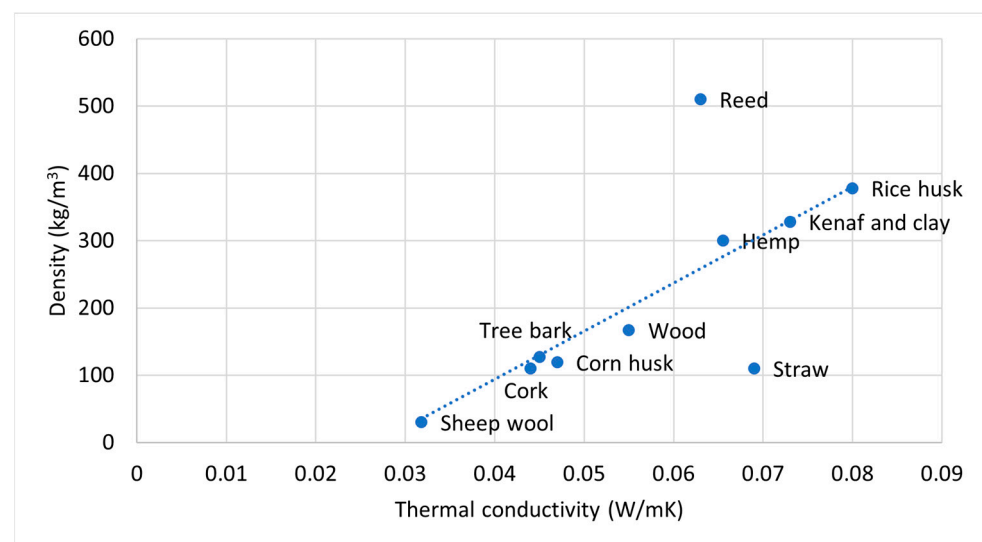


Figure 5. Relation between density and thermal conductivity.

Viel, Collet, and Lanos [45] stated that thermal conductivity may depend on the density but is also impacted by the type of binder used in the material.

The use of binder aggregates must be studied, as it can cause changes in thermal conductivity. A composite with hemp shiv and polyvinyl alcohol (PLA) showed a higher

thermal conductivity than other samples without any binder [45]. However, any mix with hemp shives still has lower thermal conductivity than corn cob residues [45].

Using natural fibers as aggregates can improve other physical characteristics of already commercialized materials. For example, Guna et al. [46] managed to improve airborne sound insulation and lower the thermal conductivity by 70% by adding mulberry stems on a gypsum board for ceiling applications.

3.2.2. Heat Capacity, Effusivity, and Diffusivity

Regarding the thermal effusivity property, Cottrill et al. [47] highlighted that thermal effusivity is still quite unexplored, and studies tend to focus on improving thermal conductivity only. This fact corroborates the results of this review, since only two publications mention effusivity values. Muthuraj et al. [38] identified that a rice husk composite has lower thermal conductivity (0.08 W/mK) among other materials and also has a lower effusivity, meaning less thermal energy exchange.

Salazar et al. [48], through an innovative measurement method, confirmed that as the porosity of a material increases and, consequently, the density lowers, the thermal effusivity decreases, moving close to air effusivity. While air thermal effusivity is $5.5 \text{ W}\cdot\text{s}^{1/2}/\text{m}^2\text{K}$, XPS has a thermal effusivity of $54 \text{ W}\cdot\text{s}^{1/2}/\text{m}^2\text{K}$, and the cork insulation board presents a value of $180 \text{ W}\cdot\text{s}^{1/2}/\text{m}^2\text{K}$ [48].

Only two publications addressed the relationship between thermal conductivity and heat capacity characteristics, and divergent results on the relationship lead to a point to be further explored. On an almond skin composite, thermal diffusivity and heat capacity were measured, and the study revealed that the best solution (almond skin, gum Arabic, and water) concerning thermal conductivity had the lowest thermal diffusivity ($0.18 \times 10^{-6} \text{ m}^2\text{s}^{-1}$) and the highest volumetric heat capacity ($0.416 \times 10^{-6} \text{ J}/\text{m}^{-3}\text{K}^{-1}$) [49]. On the other hand, oven-dried wood waste presenting a lower density ($117 \text{ kg}/\text{m}^3$) and lower thermal conductivity (0.0528 W/mK) showed the lowest volumetric heat capacity ($0.1026 \times 10^6 \text{ J}/\text{m}^3\text{K}$) and higher thermal diffusivity ($0.5153 \times 10^{-6} \text{ m}^2\text{s}$) among other samples with the same material [32]. Heat capacity and diffusivity are inversely proportional, yet just a few studies addressed these properties, and, thus, more research should be performed on their relationship with thermal conductivity and density.

Some manufacturers do not make clear the diffusivity value but, instead, present the time lag of the material, i.e., how long heat takes to pass through. For example, rice straw panels [50] have a time lag of 10:30 h for 300 mm thickness, which shows a good heat capacity of the material and, therefore, a great thermal diffusivity.

3.2.3. Water Absorption

A few research studies show water-related features. These studies usually consider water absorption after 24 h of the immersed material, with a value expressed as a percentage.

A sample of wheat straw and clay had about 0.02% of moisture content after one hour immersed in water and about 0.06% of moisture content after 24 h [51]; this is due to the hydrophilic characteristic of clay used in the research. Still, wheat straw bale, known for its good thermal performance, showed an initial moisture content of 11 to 16% and water absorption of 65% to 75% [52]. Biomass fibers of wheat straw of a density of $0.312 \text{ kg}/\text{m}^3$ had a water absorption rate of 365%, while seagrass fibers of $0.721 \text{ kg}/\text{m}^3$ showed 293% of water absorption [42]. Water absorption is affected by the particle sizes of the specimen, with smaller particles leading to higher water absorption [35]. Regardless of the material, water absorption also varies according to the type of processing and how the material is presented, as additives and previous handling can completely alter the final characteristics.

Arundo donax reed composite had a water absorption rate from 57.3% to 88.16% [53], while the raw material reached just 52.6% [29].

The lowest presented value of water absorption came from the mussel shell, from 2.17% to 2.56% [39].

3.2.4. Water Vapor Permeability

Specialist builders agree that insulation and coatings must maintain the permeability and breathability of walls, as in vernacular buildings [54]. Thermal insulation should provide fast moisture redistribution to avoid condensation zones [15].

Research on five bio-based materials for insulation (wood fiberboard, flax fibers, hemp fibers, jute fibers, and sheep wool) concluded that other than good thermal conductivity values, they have a high moisture diffusivity, comparable to hydrophilic mineral wool, therefore, allowing one to avoid the use of water vapor barriers [15]. Lafond and Blanchet [55] compared bio-based insulation materials with expanded polystyrene and concluded that thermal conductivity can have the same range, but vapor permeability tends to be up to three-times better, depending on the geometry of internal structures.

On manufacturers' datasheets of products, instead of addressing water absorption, they usually mention the water vapor diffusion resistance factor (μ -value).

Regarding commercialized products, the water vapor coefficient varies from 1 μ to 2 μ for most natural materials, for example, for grass insulation [56], but reaches 200 μ for extruded polystyrene [57]. Although grass insulation and extruded polystyrene have similar values for density and thermal conductivity, their behavior towards water and moisture is completely different. Despite higher water absorption rates in natural fibers, which can increase thermal conductivity, using breathable insulation will prevent the risk of condensation and mold and, therefore, promote better indoor air quality.

In academic research, no references to vapor permeability were found, which identifies a research gap in the field.

3.2.5. Fire Resistance

Considering fire resistance, very little academic research addresses this topic. Although natural insulation materials may be considered combustible, in certain conditions, they are safer than conventional insulation materials. For example, they release less smoke during combustion in comparison to expanded polystyrene, which can produce 32-times more smoke than wood batt insulation [55].

On a compressed product such as a straw bale, an optimal fire resistance can be achieved. During a 15 min fire resistance test, a straw bale sample of 108 Kg/m³ density with a 5 mm clay plaster layer had its straw charred to a 55 mm depth only and did not spread flames due to its high density [58].

Two publications that address polypropylene and polystyrene composites classify fire resistance by the American standard UL94 for plastic flammability [46,59]. Once a composite of 90% sheep wool and 10% polypropylene has a V-0 rate [59], indicating that burning stops within 10 s on a vertical part, mulberry composites have a rate from V-1 to V-2 [46], meaning that burning stops within 30 s on a vertical part, allowing for non-flammable and flammable drops of plastic, respectively.

Following the standard expected in the methodology, despite a fire resistance classification of Euroclass E for most materials' specifications, some materials already installed, with plaster or inside walls, can present a better classification. For example, strawbale covered by plaster presents a classification of Euroclass B/S1/d0, according to its EPD [60].

To summarize the topic of physical parameters, Table A1 in Appendix A shows an overview of parameters found in the literature.

3.3. Mechanical Parameter Analysis

Most academic publications address the mechanical behavior of developed products to evaluate their durability and to determine for which building elements they are suitable, such as floors, ceilings, or walls.

As a normal tendency in conventional building materials, the mechanical properties improve proportionally to the material's density [61]. However, for mixed materials, this is not always true, as one element can weaken the other [61], which is usually the case with natural fiber composite materials.

Table 2. Cont.

Studied Material	Density (kg/m ³)	Compressive Strength (MPa)	Flexural Strength (MPa)	Tensile Strength (MPa)	Modulus of Elasticity (MOE) (MPa)	Modulus of Rupture (MOR) (MPa)	Ref.
Flax shives particles board	500	12.40	-	0.60	1722	13.85	[62]
Cotton/Denim natural fibres insulation board, Inno-Therm/Métisse	20–25	-	-	0.0071 MPa (longitudinal), 0.0007 MPa (parallel)	-	-	[70]
Grass insulation, Gramitherm	40	-	-	>0.02 MPa	-	-	[56]
Extruded Polystyrene (XPS) Danopren	32.41	0.3	-	-	-	-	[57]

¹ Two layers of reed (4 cm) perpendicular to each other.

3.4. Environmental Parameter Analysis

Regarding the importance of the environmental impact assessment discussed above, some publications highlight the importance to consider it [23,37,71], but only a few present values for the environmental performance of the products studied.

Rojas et al. [23] highlighted that the embodied energy from the use of wheat straw would be recovered in the second year of the building, i.e., in less than 5% of the building's lifetime.

Considering a lifetime of 60 and 30 years, a novel bio-insulation composite has a biogenic carbon of 54 and 49 gCO_{2-eq} resulting in a positive Global Warming Potential value of 30 and 36 gCO_{2-eq}, respectively, due to the manufacturing process involved [71]. Carcassi et al. [71] raised attention to the importance of a longer lifetime of bio-based insulation products to maintain high carbon sequestration in buildings. Despite being an interesting idea to grow building products such as mycelium-based insulation, the final product still has a disadvantage compared to other bio-based insulation products, namely the need for a higher thickness to achieve the same insulation and a slightly higher potential environmental impact when compared to negative-carbon materials such as straw.

The use of bio-based materials should be considered in locations close to where they are harvested to avoid unnecessary transportation and, consequently, possible environmental impacts. Parlato, Porto, and Valenti [25] evaluated the resource availability in Italy and concluded that raw sheep wool waste could generate around 1.5 million soft mats, fulfilling the Italian market demand, which, nowadays, imports its products from different countries.

A dynamic life cycle analysis that includes embodied biogenic carbon showed that fast-growing biogenic materials, such as discarded biomass from agricultural crops, can lead to a significant reduction in greenhouse gas emissions [11]. Land available for growing wood and straw can provide enough materials for the European renovation market. However, hemp and cork can only supply a local market, since a large-scale supply chain is not reasonable [72].

Table 3 consists of values from existing insulation materials extracted from several databases, considering the product stage from A1 to A3, namely raw material acquisition and manufacturing.

Environmental Product Declarations (EPDs) from different databases were used in this analysis as no academic research showed a clear method to evaluate the presented environmental parameters. For the comparison, we used a functional unit of 1 m² with a thermal resistance of 2.5 m²K/W.

Among the analyzed materials, wheat straw bale and grass insulation need to have the greatest thickness, 12 and 10.25 cm, respectively, to achieve a thermal resistance of 2.5 m²K/W. On the other hand, the polyurethane (PU) rigid panel, expanded polystyrene (EPS), and extruded polystyrene (XPS) only need a thickness of 5.5, 7.5, and 8.5 cm, respectively, to achieve the same performance.

Table 3. Environmental performance of insulation materials.

Material	Total Primary Energy Use (MJ)	Global Warming Potential (KgCO ₂ eq.)	Biogenic Carbon (KgC)	Reference
Polyurethane rigid panel 100 mm Knauf Thane Mur B2i	1.57×10^2	6.93×10^0	0.00	[73]
Expanded Polystyrene (EPS), Knauf Xtherm Ultra	9.75×10^1	2.83×10^0	0.00	[73]
Extruded Polystyrene (XPS) Danopren	1.46×10^2	6.43×10^0	0.00	[57]
Wood fibre insulation board, Gutex thermoflex	1.75×10^2	-2.88×10^0	1.88	[73]
Wood fibre insulation board, STEICO Flex	1.65×10^2	-5.55×10^0	2.10	[73]
Expanded Cork Board for internal thermal insulation, French ministry for ecological transition	3.72×10^3	1.65×10^1	8.26	[73]
Sheep wool batt, Havelock wool	1.79×10^2	6.58×10^0	22.50	[74]
Cotton/Denim natural fibres insulation board, Inno-Therm/Métisse	2.78×10^1	2.42×10^0	--	[73]
Rice straw, FBT isolation	1.67×10^2	-2.54×10^0	1.57	[73]
Sheep wool loose-fill insulation, havelock wool	6.45×10^1	4.40×10^0	22.50	[74]
Hemp wool, Technichanvre	1.74×10^2	-2.11×10^0	0.86	[73]
Expanded Insulation Cork Board, Amorim isolamentos S.A.	7.77×10^2	-1.98×10^1	--	[75]
Grass insulation, Gramitherm	2.02×10^2	-8.04×10^0	1.97	[73]
Wheat Strawbale from conventional agriculture	1.86×10^2	-1.69×10^1	4.78	[73]

Nevertheless, when primary energy use is considered, expanded corkboard, grass insulation, and wheat strawbale have the highest values, probably due to the harvest process involved. The lowest values for primary energy use stand with the insulation board with cotton and denim natural fibers, as well as sheep wool loose-fill insulation, followed by conventional insulation, EPS, XPS, and PU rigid panels.

Concerning global warming potential, the lowest values were among straw, grass, wood fiber, and hemp wool, probably due to the high biogenic carbon once GWP presents as negative values. As expected, conventional materials have the highest values.

It is important to highlight expanded corkboard insulation values for GWP. The value on the EPD from a Portuguese manufacturer presented the lowest value from the table; this can be deduced already considering the biogenic carbon, since the value is negative and no information on biogenic carbon alone is mentioned. On the other hand, information on the same material from the French Ministry for ecological transition, generic data provided due to the lack of national EPD, shows the highest value for GWP and without information on the origin of the material. From these data, we can point out the importance of using specific manufacturing information instead of generic data that can lead to mistakes in the final evaluation.

Some materials addressed in academic research as possible insulation materials, such as reeds and leaves of various plants, did not have EPD or environmental assessment, making comparison impossible.

Regarding the environmental analysis of insulation materials, natural materials stand out, especially fast-growing plant fibers due to their biogenic carbon. The shift in mindset from using conventional materials to using natural materials that can store more carbon and compensate for emissions is promoting the use of bio-based materials, as in the normal life cycle scenario of plant carbon would return to the atmosphere in a shorter time. Biogenic carbon emissions are related to the time needed for biomass regeneration [76]. Fast-growing bio-based materials can help to compensate for carbon emissions, as it is nearly impossible to have zero embodied GHG emissions, especially due to highly processed materials still being needed in some foundations and as a stabilizer for some materials [77]. Keena et al. [78]

highlighted that bio-based solutions for built environments have lower environmental impacts, in a life cycle approach, per functional unit than other conventional solutions.

4. Conclusions

This review highlighted the extensive nature of bio-based insulation materials and their multitude of combinations. Despite the great number of publications found in the bibliographic databases, most of them are focused on conventional materials or improvements in materials based on synthetic components. The characterization of natural materials should be made to promote the least processed materials possible.

Many times, natural materials are treated as aggregates for composites, despite some findings that show that raw materials provide better thermal performance, as for sheep wool [25]. Potential bio-based insulation materials should be tested in their raw form and then with different binders, preferably natural, to improve their mechanical, functional, and environmental characteristics.

Additionally, few research studies addressed the environmental performance of bio-based insulation materials. More comprehensive environmental studies will highlight the environmental advantages of using this type of material, which would contribute to promoting its use. It is seen that ecological innovations can replace conventional materials and ensure the same energy efficiency during the operation phase of buildings.

The results obtained provide an overview of recent studies and identify a gap in research for an environmental impact assessment on insulation materials. There is a gap concerning the number of environmental product declarations between conventional insulation materials, such as XPS and EPS, and bio-based unconventional insulation materials, such as natural fibers. Research on this matter must be conducted to provide information for future EPDs on bio-based insulation materials.

A lack of characterization of thermal mass and thermal inertia, which can be characterized by the heat capacity and diffusivity parameters, was also identified among recent publications, providing better solutions for constructions, especially those for the renovation of vernacular buildings. The complete characterization of the applied material and that to be applied allows for the simple and low-cost renovation of the building stock, without pathologies, such as extreme condensation and poor use of the passive energy efficiency potential generated by the materials used. As building rehabilitation is an important topic in current and future regulations, it is important to think of vernacular buildings as an opportunity to produce healthier housing through natural materials.

Since the most recent European building directive, EBPD recast 2022 [7], aims to reduce life cycle greenhouse gas emissions and energy consumption by setting energy and CO₂ emission performance targets, it encourages the development of environmentally friendly products.

The research findings disclosed the potential of using natural fibers as insulation materials. However, further research is needed focusing on the life cycle assessment of new products to make them adequate for future regulations. Based on the outputs of this study, some recommendations can be made for future research:

- To analyze the heat capacity of materials as a way to understand long-term thermal behavior and explore the decrement delay of materials;
- To use natural binders and optimize manufacturing processes to reduce potential environmental impacts;
- To perform a cradle-to-cradle life cycle assessment of existing insulation materials to better understand their impacts and how they fit into the circular economy targets.

This review concludes that bio-based insulation materials have significant potential to improve building performance, fulfil requirements, and promote a more sustainable industry, despite further needed work.

For future research, it is suggested to include other parameters in the analysis, such as local availability, cost-effectiveness, and potential applications of bio-based insulation materials for several types of buildings.

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Appendix A

Table A1. Physical characteristics of reviewed materials.

Studied Material	Density (Kg/m ³)	Thermal Conductivity (W/mK)	Specific Heat Capacity (J/Kg·K)	Thermal Stability (°C)	Effusivity (Ws ^{1/2} /(m ² K))	Diffusivity (m ² /s)	Water/Moisture Absorption after 24 h (%) or Water Vapour Diffusion Resistance (μ-Value)	Fire Resistance	Ref.
Wheat Strawbale, stalk orientation perpendicular to heat flow	86.42–135.09	0.066–0.071	-	-	-	-	-	Non-combustibility	[58]
Wheat Strawbale, stalk orientation parallel to heat flow	91.82–114.46	0.077–0.084	-	-	-	-	-	Non-combustibility	[58]
Wheat Strawbale	126–129	0.078–0.056	-	-	-	-	-	-	[24]
Wheat straw and clay	343–567	0.07–0.079	-	-	-	-	-	-	[51]
Wheat straw insulation panel	235–894	0.092–0.186	-	-	-	-	32–102%	-	[43]
Wheat straw	105–112	0.046	-	-	-	-	-	-	[23]
Konjac glucomannan/starch-based aerogel strengthened by wheat straw	43	0.04641	-	-	-	-	-	-	[64]
Untreated Rice straw particle board	500	0.086	-	-	-	-	-	-	[62]
Eucalyptus Globulus leaves and wheat straw fibres	217	0.049–0.065	-	-	-	-	-	-	[65]
100% Sheep wool soft mats	30	0.0318	-	-	-	-	-	-	[25]
80% sheep wool 20% polyester fibres semi-rigid panel	25	0.04	-	-	-	-	-	-	[25]
100% Sheep wool loose-fill fibres	75–100	0.035	-	-	-	-	-	-	[25]
90% sheep wool, 10% polypropylene	-	0.058–0.083	-	250, 1% weight loss until 250 °C	-	-	21–34%	Fire retardant rate of V-0 according to UL-94 rating	[59]

Table A1. Cont.

Studied Material	Density (Kg/m ³)	Thermal Conductivity (W/mK)	Specific Heat Capacity (J/Kg·K)	Thermal Stability (°C)	Effusivity (Ws ^{1/2} /(m ² K))	Diffusivity (m ² /s)	Water/Moisture Absorption after 24 h (%) or Water Vapour Diffusion Resistance (μ-Value)	Fire Resistance	Ref.
Flax shives particles board	500	0.099	-	-	-	-	-	-	[62]
Cotton/Denim natural fibres insulation board, Inno-Therm/Métisse	20–25	0.039	1600	-	-	-	Water vapour diffusion = 2.2 μ	Euroclass E	[70]
Wood fibre insulation board, STEICO Flex	60	0.036	2100	-	-	-	Water vapour diffusion = 2 μ	Euroclass E	[82]
Expanded Insulation Cork Board, Amorin	130	0.040	-	-	-	-	-	Euroclass E	[75]
isolamentos S.A. Grass insulation, Gramitherm	40	0.041	1500	-	-	-	Water vapour diffusion = 1 μ	Euroclass E	[56]
Wheat Strawbale from conventional agriculture	100	0.048	1558	-	-	-	Water vapour diffusion = 2 μ	Euroclass E	[83]
Sheep wool insulation, Optimal	18	0.038	1760	-	-	-	Water vapour diffusion = 1 μ	Euroclass D	[84]
Lehner Isolena Extruded Polystyrene (XPS) Danopren	32.41	0.034	--	-	-	-	Water vapour diffusion = 200 μ	Euroclass E	[57]

¹ Two layers of reed (4 cm) perpendicular to each other.

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