Biomass Conversion and Biorefinery
https://doi.org/10.1007/s13399-023-05192-8

REVIEW ARTICLE

Promising biomass waste–derived insulation materials for application in construction and buildings

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Received: 30 August 2023 / Revised: 21 November 2023 / Accepted: 28 November 2023

Abstract

Current insulation materials applied in construction engineering and the building industry are generally petrochemical-based polymers and recycled thermal insulation materials. The environmental effects of these materials' production processes are substantial, despite their high thermal insulation performance. Consequently, the researchers conclude that it is essential to develop and produce insulating materials with superior thermal properties, minimal environmental impact, and a reasonable cost. The study concentrated on the application of insulation materials derived from biomass in the development of thermal insulation. The purpose of this review is to investigate and develop the possibilities of using biomass wastes as renewable and eco-friendly thermal insulation materials for construction engineering and the building industry. The thermal conductivity of those materials was measured using the hot plate and hot box methods, two of the most widely used hot processing methods. With a relatively low thermal conductivity ($< 0.100\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$), this review provides critical scientific insight into potential building insulation materials derived from biodegradable and abundant resources. It was observed that these materials are appealing for use in building and construction because they have a number of potential advantages from technical, economic, environmental, and green credentials perspectives. The collection of information enables some conclusions regarding the different biomass waste–derived insulation materials that have already been investigated and identifies gaps in the literature. Finally, the scope of commercialization pathways and future research directions to validate the proposed material alternatives' claim for commercial-scale applications has been identified in this review.

Keywords Thermal conductivity · Building insulation materials · Biomass valorization · Hot plate method · Hot box method

Abbreviations

HB_M	Hot box method
HP_M	Hot plate method
TC	Thermal conductivity

1 Introduction

The present tendency in the building industry to decrease and safeguard environmental effects necessitates the design and production of more ecological and sustainable building materials [1, 2]. As a result, it is a crucial goal of the modern building industry to research environmentally friendly and efficient insulation materials, and biomass insulation materials will be promising. Biomass waste–derived materials have emerged as one of the alternatives that can be used to develop thermal insulating materials, as has become increasingly clear [3–5].

One of the goals established by the European Union in its roadmap to a low-carbon economy by 2050 is to reduce energy use in buildings. In comparison to 1990, CO_2 emissions must be reduced by 80–90% by 2050 if the world's temperature rise is to be limited to 2 °C [6, 7]. Additionally, heating and cooling space in buildings consumes more than 10% of world energy [8], while producing close to 30% of global CO_2 emissions. Enhancing a building's thermal insulation capacity is one of the most cost-effective ways to reduce energy usage in buildings [8].

In the coming years, the use of environment-friendly and renewable wastes will improve energy efficiency and thermal

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insulation of buildings which can, in turn, reduce the negative environmental consequences (e.g., greenhouse gas emissions, climate change, and impoverishment of resources) [9–12] and contribute significantly to sustainability. These environmentally friendly and long-lasting insulation materials are in keeping with the trend toward low-carbon and positive-energy buildings [13–15].

Thermal insulation materials have a crucial role in reducing energy consumption and ensuring an appropriate indoor environment. As a result, improving the thermal insulation property of the building sector is critical, particularly by enabling energy savings through the decrease of energy losses for heating-cooling purposes. It is widely acknowledged that the quality of thermally insulating material is generally determined by a number of significant factors, including low TC, renewability, cost-effectiveness, and use of environmentally acceptable resources. In this context, biomass waste–derived materials may be more appealing than other conventional insulating materials since they can meet these criteria [16, 17]. TC as one of the most fundamental features of a thermally insulating material [18–20] is a well-known important measurement of building materials used in housing, wall systems, commercial buildings, and industries and is commonly decreased to achieve improved energy efficiency [21–23]. In the context of green thermal insulation materials, natural renewable biomass, i.e., Washingtonia plant biomass biochar [24]; sawdust wastes [25]; agro-industrial [26, 27] and agricultural wastes [28–42]; banana fiber [43]; wheat straw [44]; *Caryota urens* and coconut husk biomass–derived biochar [45]; oil palm empty fruit bunch and sugarcane bagasse fibers [46]; pineapple leaf fiber [47]; narrowleaf cattail [48]; polysaccharide-based aerogels [49]; sequoia, pine, white wood, cherry, gum, walnut, white oak, brown ash, and red birch [50]; Acai berry residues [51]; discarded wool and poultry feathers [52]; biomass-fired fly ash [53]; hazelnut shells, pinecone, paper, and sheep wool [54]; olive residue, willow, wood pellets, wheat straw, rape straw, miscanthus, and torrefied pine [55]; and balsa wood [56], is attractive due to its distinctive physicochemical features such as renewability, biodegradability, and low TC and can also have a net reduction in CO_2 emissions.

Furthermore, solid agricultural wastes such as wheat brand, sugar beet pulp, and rice polish may be used as biosorbents for the removal of heavy metals from wastewater [57, 58]. As opposed to that, recycled plastics (e.g., polyethylene terephthalate, high-density polyethylene, polyvinyl chloride) [59–64] and petrochemical oil/coal-derived polymers with low TC (< 0.100 $W\cdot m^{-1}\cdot K^{-1}$), such as expanded polystyrene, extruded polystyrene (e.g., Styropor® with 0.045 $W\cdot m^{-1}\cdot K^{-1}$) [65], polyurethane, polyethylene, and phenol formaldehyde resins, might have some drawbacks which are flammability, non-renewability, and high toxicity index (see Fig. 1) pertaining to the release of hazardous gases (e.g., CO, CO_2, NO_x) [59–61]. It can be seen that there are numerous significant issues that prevent the insulation materials currently used in buildings from developing in a sustainable way. The development of a novel, promising material for building insulation is therefore imperative.

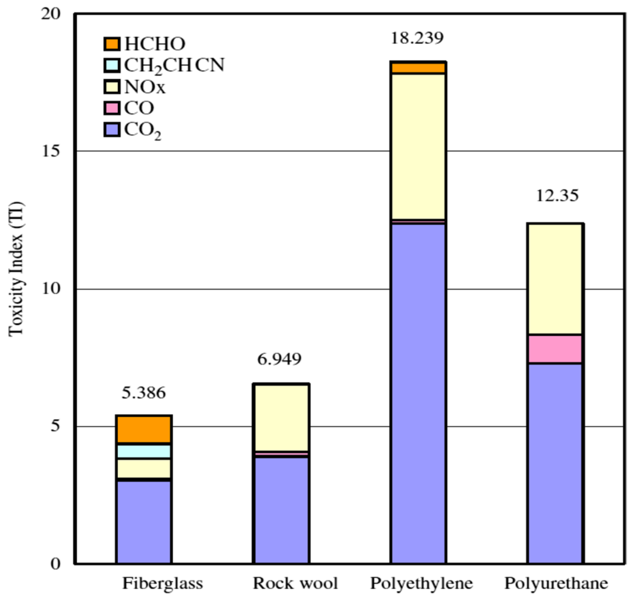

Fig. 1 Average value of toxicity index (with permission from [59])

In order to show the value-added of natural biomass wastes for environmentally friendly and sustainable construction industries, this review intends to examine the thermal properties of various insulation materials obtained from biomass wastes, specifically, TC evaluated using hot processing methods (i.e., hot plate and hot box). It is believed that such a review will provide a critical scientific understanding of biomass wastes obtained from biodegradable and renewable resources, allowing for the production of "green" building materials for environmental protection.

2 State of the art of biomass waste–derived insulation materials

The most widely used categories of building insulating materials are natural biomass wastes, recycled materials, and petrochemical polymers, illustrated in Fig. 2. Typical insulating materials have specific limits because they are environmentally unfriendly, non-biodegradable, mechanically less stable, and made from non-renewable resources. The performance of natural biomass wastes as thermal insulators is the main subject of this review (Fig. 3).

In comparison to existing thermal insulation materials (Fig. 4), biomass waste, such as spruce needles, performs as well as or better than most. These properties are similar

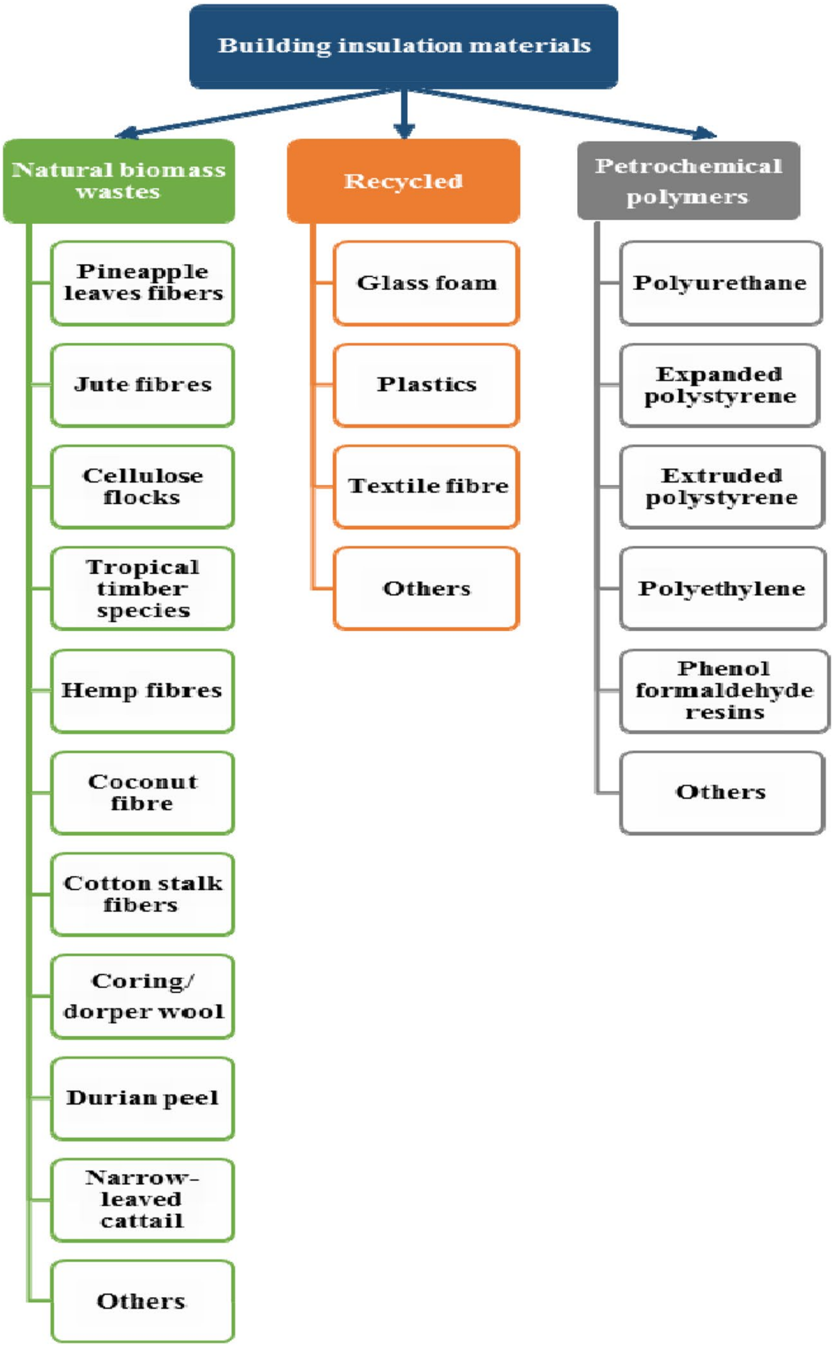

Fig. 2 Schematic illustration of building insulation materials

to those of extruded foam polystyrene, mineral and stone wool, and other thermal insulation materials [66].

TC is affected by the material's mean temperature and moisture content. It expresses a material's heat-conducting capacity [67]. The TC of several of these biomass waste–derived insulation materials is compared to conventional lower-density insulation materials in Fig. 5 [36]. In general, higher-density materials have higher TC under the same conditions. This is mostly due to decreased air content and a decrease in the size of the air inclusions associated with increasing density when heat movement through the samples is via the solid particles [67].

3 TC of biomass waste–derived insulation materials

The TC (Fig. 6) is a parameter of a building insulation material that expresses the ability to transfer heat (Q) of the insulating materials which are placed between two

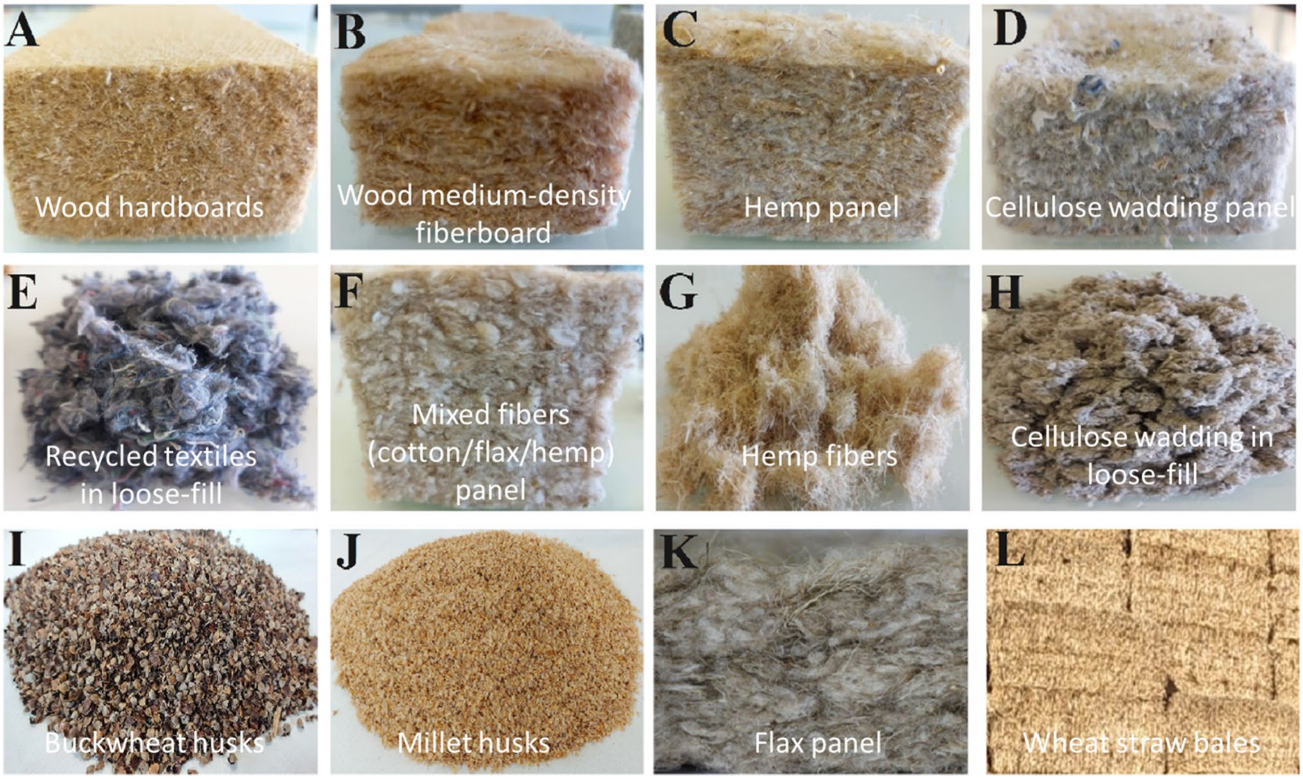

Fig. 3 Various biomass-based insulation materials and products (with permission and recreated using data published in [13])

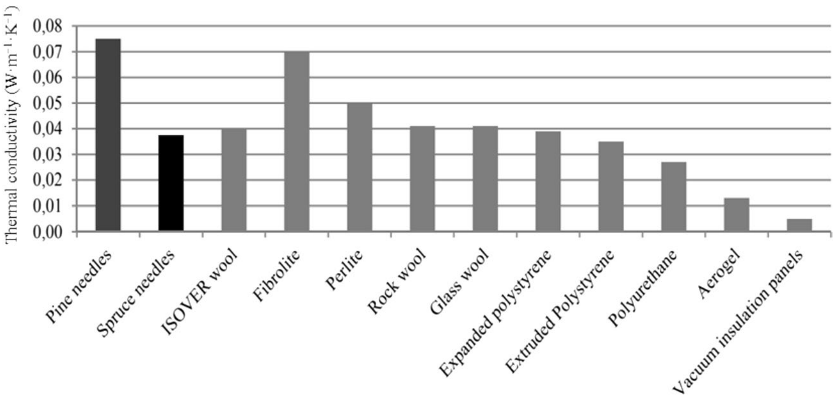

Fig. 4 TC of organic and inorganic materials (with permission and recreated using data published in [66])

reservoirs at different temperatures (T_2 and T_1), across a surface area (m^2) perpendicular to the source. It is directly influenced by the composition of the material, the environment's temperature, the porosity, and the heat current's direction. The TC of the building materials should be evaluated using accurate experimental methods like hot plate (HP_M) and hot box (HB_M) methods, often used in different research efforts worldwide. The HP_M [68–72] is commonly used for the measurement of TC of homogeneous/multilayer materials and composites. In contrast, the HB_M [73–75] is a very popular technique to measure not only TC of homogenous and composite materials but also large and inhomogeneous components like doors, thermal bridges, and windows [76–80]. These two methods may be substantially equivalent in the considered range of TC measurements. They are not entirely interchangeable, though, when it comes to different kinds of sustainable biomass wastes.

Recently, Li and Huang [8] investigated natural and renewable pine sawdust from wood processing as a new biomass-based thermal insulating material with low TC (0.062 $W\ m^{-1}\ K^{-1}$). In order to prepare biomass-based materials for thermal insulation for buildings energy savings, this work offers a facile, green, and affordable method.

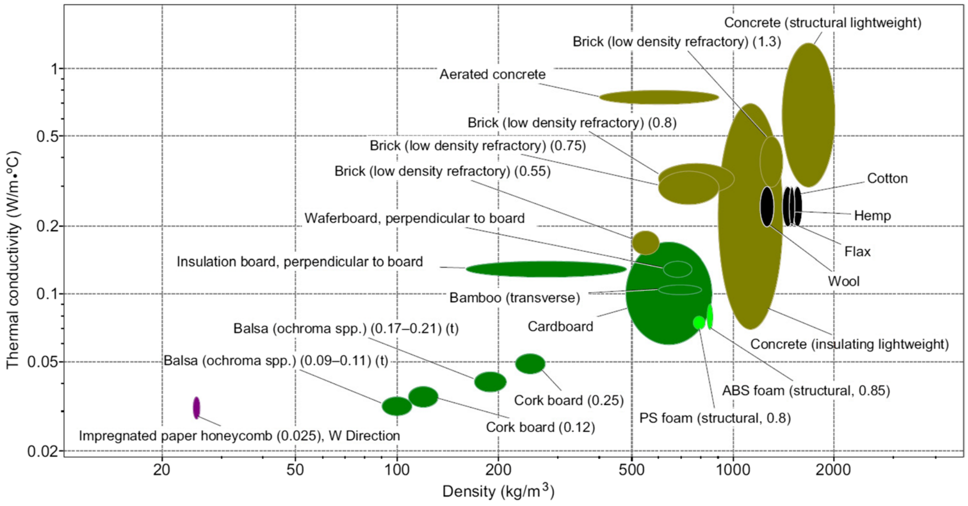

Fig. 5 TC versus density for biomass waste–derived materials (with permission from [67])

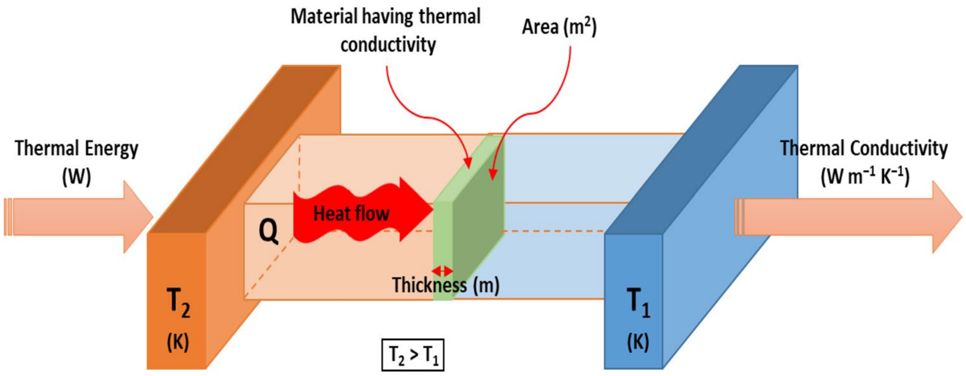

Fig. 6 Schematic illustration of the TC measurement

Luamkanchanaphan et al. [48] showed that insulating boards derived from narrowleaf cattail (*Typha angustifolia L.*) fibers with relatively low TC (0.044–0.061 W m^{-1} K^{-1}), have good mechanical and physical properties and can also be used as a promising insulator of a wall, ceiling, and other building materials for energy saving.

Novais et al. [81] evaluated biomass waste valorization using a simple and cost-effective production process of porous biomass coal fly ash–based geopolymers with tailored TC to make construction partition boards and wall panels. Mechanical resistance, TC, and porosity of these materials can all be changed simply by the amount of hydrogen peroxide used as a pore-forming agent.

Binici et al. [82] examined the production of lightweight construction materials with biomass wastes (chipboards, cotton waste, and fly ash) with very low TC (0.023 W m^{-1} K^{-1}), which might be used for significant energy savings in buildings.

Stapulionienė et al. [83] presented the manufacturing possibilities based on biologically divisible and easily processed natural porous fibers (long and short, hemp and combed hemp, flax and combed flax; and chopped, peat, hemp, and flax) supplied by the agriculture. These fiber materials with useful thermal insulation properties (TC: 0.034–0.060 W m^{-1} K^{-1}) could be used for the production of loose-fill thermal insulating material.

However, Kymalainen and Sjoberg [84] suggested that natural resources like bast fibers (e.g., flax and hemp) are suitable for thermal insulation, but have also some drawbacks associated with sensitivity to moisture and risk from other contaminants and microorganisms, and for these reasons, their quality should be monitored regularly.

Korjenic et al. [85] investigated different insulation plates from natural fibers (flax, jute, and technical hemp). In contrast to conventional insulation materials like polyurethane, polystyrene, or mineral wool, the authors claimed that the correct combination of biomass materials with low TC (0.039–0.049 W m^{-1} K^{-1}) is unquestionably an acceptable substitute.

Dikici et al. [86] examined the TC of various biomass products (Bermuda grass seeds and wild flower seeds) at varied moisture content. The TC of Bermuda grass seed varied from 0.082 to 0.146 W m^{-1} K^{-1}, with a moisture content range of 0–30% wet basis. The TC of wildflower seeds varied from 0.098 to 0.218 W m^{-1} K^{-1}, with a moisture content range of 0–30% wet basis. For moisture variation, a linear increase has been observed because of the fact that water has a higher TC than biomass samples and causes a rise in the overall TC of the sample. TC of Bermuda grass seed and wildflower seed will be evaluated for the possibility of using them for insulation and other applications based on clean energy such as biomass conversion and combustion.

Reif et al. [87] checked different kinds of thermally insulating materials derived from natural fibers (i.e., hemp, straw and cellulosic fibers, and their mixtures) at various humidity conditions (0%, 50%, and 80%). The best TC (0.048–0.046 W m^{-1} K^{-1}) of all tested materials and mixtures was achieved at 0% humidity (dry materials) which is connected with different hygrothermal behavior of natural-fiber materials.

Previous research [88] presented natural insulating materials derived from straw bale, treated and untreated sheep wool, hemp fiber, wood fiber, and flax fiber (TC: 0.048–0.065 W m^{-1} K^{-1}), which can be used for building roofs, envelope walls, or ceiling composition.

Vaivare et al. [89] determined TC (0.034–0.073 W m^{-1} K^{-1}) of biomass wastes derived from apple tree leaves, which can be used as an additive for construction materials.

Furthermore, Muizniece and Blumberga [90] evaluated the addition of different kinds of adhesive materials (i.e., potato starch adhesives, dried needles, and needles with small branches) to prepare plate-type thermal insulation materials with comparatively low TC (0.048–0.055 W m^{-1} K^{-1}).

Andoh et al. [91] examined a solar water heater designed with coconut coir with relatively low TC (0.074 W m^{-1} K^{-1}) as an insulating material. So, the low cost of this type of solar water heater and its attested good thermal performances show that this material is a good alternative material to conceive new solar water heaters at reasonable prices.

3.1 Hot plate method (HP_M)

As mentioned earlier, the HP method (especially guarded-HP_M [92] which may include a single and double specimen) is the most significant and frequently used technique to determine the effective measurement of TC of homogeneous/multilayer materials and composite specimens (Table 1). The guarded hot plate setup for two specimens (Fig. 7) requires a double-sided heat flow configuration and the plates (i.e., cold/hot and guarded hot plates located on the sides), which are arranged symmetrically between these specimens. Temperature control system (T_h temperature on the hot side, T_c temperature on the cold side, T_c ($<T_h$); and auxiliary guard heater which controls T_m (temperature of material (specimen)), $T_m = (T_h + T_c)/2$) is used to minimize heat leakage near the edge of the specimens or boundaries and maintain proper heat flow by differential thermocouples [93–95].

Recently, Tsalagkas et al. [25] investigated overlaid bark-based panels with low TC (0.067–0.074 W m^{-1} K^{-1}) which displayed promising characteristics as insulation materials. Along with being used to make ceiling and wall insulation, this material for insulation can also be utilized to produce furniture [81, 82]. Khedari et al. [96] presented agriculture waste to produce new particleboards obtained from durian peel (TC: 0.073 W m^{-1} K^{-1}).

Worth mentioning is the work by Panyakaew and Fotios [97] on the production of novel insulation boards derived from environmentally friendly waste materials like bagasse and coconut husk (TC: 0.046–0.055 W m^{-1} K^{-1}). According to the research, coconut husk boards exhibit stronger water resistance than bagasse boards, which is crucial for thermal insulation applications.

Xu et al. [98] created innovative binderless particleboards using a Kenaf core (TC: 0.043 W m^{-1} K^{-1}) that may be used for thermally resistant interior products, such as ceiling tiles and decorative panel substrates, as well as sound-absorbing interior products.

Limam et al. [99] indicated that TC of bio-based materials (pine wood and cork) strongly depends on wood structure, i.e., its water content and density. Moreover, the value of TC increases when the direction of the heat flow is perpendicular to the direction of its veins, which in turn contributes to the insulating properties of newly elaborated sandwich panels in building construction.

Vololonirina et al. [100] noticed that TC (0.042–0.097 W m^{-1} K^{-1}) of wood-based materials raised with moisture content and can be attributed to the heterogeneity of their nature and anisotropy (e.g., diverse origins, high and irregular porosity, presence of plant fibers, different cutting directions).

Agoudjil et al. [101] suggested that palm wood (*P. dactylifera* L.) with relatively low TC (0.083–0.084 W m^{-1} K^{-1}) will be a good candidate for safe and efficient insulating materials in the building industry (e.g., thermal insulation in roofs, walls, and floors).

By thermoforming waste from the textile industry into excellent materials for building components, Valverde et al. [102] concentrated on the preparation of new insulating materials.

Cao et al. [112] fabricated biomass-derived aerogels as potential thermal insulation components for energy-efficient buildings with low TC (0.034–0.038 W m^{-1} K^{-1}). The fully biomass-based aerogel with high mechanical modulus, flame retardancy, thermal insulation, and biodegradation showed promising prospects for building insulation materials.

Additionally, Bruijn and Johansson [103] demonstrated that a higher amount of hemp shiv in the lime-hemp mixes will give comparatively low TC (0.094 W m^{-1} K^{-1}) and

Table 1 Published TC for selected sustainable biomass wastes analyzed by HP method.

No.	Method	Biomass resource	Density [kg m^{-3}]	TC [W m^{-1} K^{-1}]	Names of the researchers/Ref
1	Guarded HP_M	Wood fiber	58	0.040	Colinart et al. [14]
2	HP_M	Poplar (*Populus* sp.) bark slabs	350	0.067–0.074	Tsalagkas et al. [25]
3	HP_M	Durian peel	856	0.073	Khedari et al. [96]
4	HP_M	Coconut husk	250–350	0.046	Panyakaew and Fotios [97]
		Binderless bagasse	250–350	0.049–0.055	
5	HP_M	Kenaf core (*Hibiscus cannabinus L.*)	150	0.043	Xu et al. [98]
6	HP_M	Algerian black cork	65	0.041	Limam et al. [99]
7	Guarded HP_M	Wood fiber	149	0.042	Vololonirina et al. [100]
		Oriented strand board	582	0.097	
		Spruce narrow rings	393	0.084	
		Spruce wide rings	368	0.095	
8	HP_M	Palm wood	254	0.084	Agoudjil et al. [101]
		(*P. dactylifera L.*)	276	0.083	
9	HP_M	Textile waste panel	203–491	0.041	Valverde et al. [102]
10	HP_M	Lime-hemp mixes	298	0.094	Bruijn and Johansson [103]
11	Guarded HP_M	Hemp fibers	38	0.044	Zach et al. [104]
12	HP_M	Cotton stalk fibers	150–450	0.059–0.082	Zhou et al. [105]
13	HP_M	Coring wool	67	0.032	Patnaik et al. [106]
		Dorper wool	59	0.032	
14	HP_M	Coconut fiber	40–90	0.049–0.058	Manohar et al. [107]
		Sugarcane fiber	40–90	0.047–0.051	
15	HP_M	Coconut fiber	174	0.048	Rodríguez et al. [108]
16	HP_M	Date palm wood powder	518	0.074–0.076	Abu-Jdayil et al. [109]
17	Guarded HP_M	Esparto	120	0.065	Bousshine et al. [110]
		Palm petiole	140	0.072	
		Chicken feathers	51	0.045	
		Sheep wool	47	0.044	
18	Guarded HP_M	Unbound wheat bran	340	0.060	Canto et al. [111]
		Banana peels	200	0.049–0.050	

steep sorption isotherms in the interval of relative humidity (95–100%) would be important in case of hygrothermal perspective of sustainable building material.

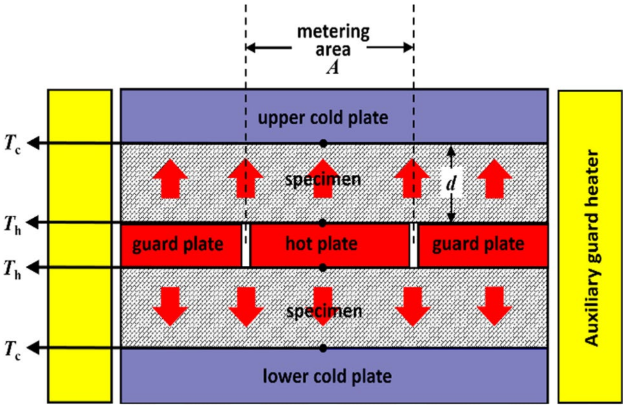

Fig. 7 Schematic representation of guarded-HP_M apparatus (with permission from [93])

To reduce the absorption of water and hygroscopicity, Zach et al. [104] proposed the potential of changing thermal insulation materials derived from natural biomass wastes (hemp fibers) by applying hydrophobic agents.

Zhou et al. [105] found that TC can be strongly correlated with the boards' density of sustainable biomass wastes like cotton stalk fibers (without resins and any chemical additives), and these materials are particularly suitable for building components (ceiling and wall applications).

Patnaik et al. [106] reported the development of green and biodegradable building materials from waste wool fibers like coring and dorper wool (TC: 0.032 W m^{-1} K^{-1}), with comparable properties to that of conventional materials.

Manohar et al. [107] investigated the prospects of using indigenous eco-friendly fibrous materials like coconut fiber and sugarcane fiber (TC: 0.047–0.058 W m^{-1} K^{-1}) as building thermal insulation.

Rodríguez et al. [108] showed that coconut fiber as a natural temperature insulation material (TC: 0.048 W m^{-1}

K^{-1}) put on the concrete in building walls (between heater and concrete) can significantly protect from high temperatures and undesirable thermal zones related to creep damage, thermal stresses, thermal fatigue, and microcracks within the comfort range.

3.2 Hot box method (HB_M)

The guarded HB_M, which is used to evaluate the thermal characteristics of homogeneous construction materials, served as the inspiration for the initial introduction of HB_M [113–115]. Compared to the guarded HP_M, which is suitable for various types of homogeneous materials, the HB_M (Fig. 8) is comparative with regard to homogeneous materials (Table 2) and inhomogeneous structures of large dimensions (as building components or building envelope assemblies) [116, 117], which are installed between a metering chamber and a climatic chamber at controlled temperatures, humidity, and airflow conditions. Additionally, the HB method can be divided into the guarded HB method with a guard chamber containing the metering box (Fig. 8a) and the calibrated HB method without a guard chamber but being calibrated with a test specimen (Fig. 8b) [118, 119].

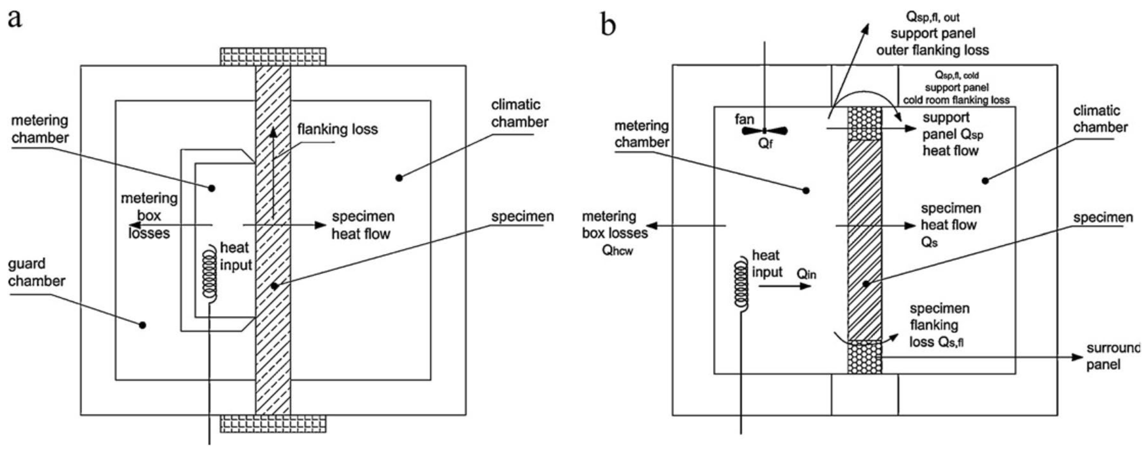

Fig. 8 Schematic representation of guarded HB_M (**a**) and calibrated HB_M (**b**) (with permission from [71])

Table 2 Published TC for selected sustainable biomass wastes analyzed by HB_M

No.	Method	Biomass resource	Density [kg m^{-3}]	TC [W m^{-1} K^{-1}]	Names of the researchers/Ref
1	HB_M	Freely patterned spruce	-	0.038	Muizniece et al. [66]
		Freely patterned pine		0.075	
2	HB_M	Tropical timber species:	888	0.057	Hata et al. [120]
		Chengal	494	0.036	
		Perupok	673	0.030	
		Nyatoh	417	0.035	
		Pulai			
3	Calibrated and guarded HB_M	Wool	10–26	0.034–0.067	Ye et al. [121]
		Wool-hemp mixtures	10–18	0.034–0.067	
4	HB_M	Cellulose flocks (panels)	60	0.039	Ricciardi et al. [122]
		Kenaf fibers	50	0.038	
		Rock wool	30	0.037	
		Jute fibers	100	0.050	
		Cork (panels)	100	0.050	
		Glass fibers	20	0.040	
		Glass wool	160	0.050	
		Waste paper and textile fibers	433	0.034	
		Mineralized wood fibers	350	0.067	
		Cellular glass	150	0.040	

Hata et al. [120] suggested that higher TC was correlated with the high materials density, and different TCs of biomass materials were meaningful for the surface temperature of these materials that were heated.

Ye et al. [121] noted that the TC of wool and wool-hemp mixtures are not significantly impacted by moisture absorption and that the average TC (0.034–0.067 W m^{-1} K^{-1}) of wool-hemp combinations did not significantly differ from insulation made of pure wool at the same density.

Ricciardi et al. [122] compared various types of natural biomass materials with traditional insulating materials, e.g., expanded polyurethane and expanded and extruded polystyrene. The researcher stated that some natural materials like rock wool, cellulose fiber, and natural pumice have a much lower value of the total energy consumption than expanded polyethylene with its highest value. Surprisingly, some types of renewable materials like rock wool (TC: 0.037 W m^{-1} K^{-1}) can be great candidates for sound-absorbing material and reversed roof insulation systems.

4 Commercialization pathways and future research directions

By demonstrating the thermal and environmental benefits of using natural biomass wastes as an insulation material, the discussed research may serve as a proof of concept. Nonetheless, in-depth research is required for the safe and effective implementation of the design and commercialization of these biomass waste–derived insulation materials.

Vacuum insulation panels (VIPs) are among the most promising materials for building insulation [123, 124] with superior ultra-low TC and thermal resistance, which were five to ten times higher compared to conventional thermal insulation materials, have garnered significant attention in recent years. Two-story retail buildings and four-story office buildings can reduce CO_2 emissions by 26.7% and 41.3%, respectively, by applying VIPs in place of traditional insulation. Using light, sustainable, and renewable kapok fibers derived from biomass, Sun et al. [125] proposed a new method for preparing VIP core materials. The produced kapok fiber VIPs had an optimal TC of 6.12 m W m^{-1} K^{-1}. By capitalizing on its high-value path of the application, it was determined that the suggested kapok fiber as a VIP core material to replace the conventional fumed silica was feasible. It is possible that the developed VIPs will be more practical to use for building thermal conservation than glass fiber and fume silica VIPs due to the superior cost-effectiveness of kapok fiber VIP over those of fume silica VIPs and even coming close to glass fiber VIPs. The long-term behavior of kapok fibers should be further investigated in future studies, though, as they represent a viable option for VIPs core material.

In order to renovate existing buildings and investigate their feasibility, Ouhaibi et al. [126] proposed new ecological material concepts that could be incorporated into residential buildings in semi-arid and cold climates. A novel approach that investigates a structural-plus-energy retrofitting solution with excellent thermal insulation properties and a loadbearing function in a residential building is proposed to mitigate summertime overheating risks and reduce energy demand. The method relies on the application of an insulating coating and the use of a recently developed material known as Poncebloc. Because 92% of this material is made up of pumice stone aggregates, it is naturally ecological. During volcanic eruptions, pumice is a naturally expanding rock that is created. Poncebloc has good thermal (TC:0.09–0.1 W m^{-1} K^{-1}) and acoustic properties, and it is naturally light. Excellent mechanical resistance is guaranteed. These findings imply that the bioclimatic building is one way to lower the amount of energy used, especially for cooling. Additionally, in semi-arid climates, the bioclimatic building is more efficient when taking energy costs into account.

Koh et al. [127] conducted a performance verification of commercially available, cutting-edge bio-based insulation material to help with the best selection and application of these materials in various conditions. Four composites of bio-based insulation (mycelium, grass, hemp, and cork) are examined for their thermal and hygrothermal properties and also simulated and examined under a range of climate profiles and typical construction details. Since cork is hydrophobic and has a low TC (0.046 W m^{-1} K^{-1}), it has been discovered to have to possess the optimal hygrothermal properties and to be appropriate in every climate that has been studied that does not support mold growth. When tested for mold growth, the hemp, grass, and mycelium-based composites exhibit degradation and comparable hygric properties. Having the highest TC (0.051 W m^{-1} K^{-1}) and being susceptible to mold growth in humid environments, mycelium-based composites perform the worst out of all the examined materials. The primary determinants of prepared insulation material's hygrothermal performance in real-world building applications are external climates and wall designs. It is discovered that, in comparison to a fully ventilated brick wall, the simulated timber frame wall with a fully ventilated cavity is better suited for low-density prepared bio-based insulation materials. According to the assembly design and local climate conditions, the study's findings highlight the suitability of using various bio-based insulation composites. They also offer guidelines for selecting the appropriate insulation material for various enclosure geometries and boundary conditions.

Various organic biomass waste materials, including cotton, rice husk, sawdust, straw, and woodchips, have been used as organic substrates in the preparation of mycelium-based composites [128, 129]. As a sustainable substitute for lightweight plastics, the direct manufacturing of natural composites using filamentous fungi that colonize lignocellulosic materials has piqued interest from academics and industry. In order to create lightweight thermal insulation, Zhang et al. [130] investigated sawdust and mycelium composites with multiscale hierarchical porous structures. Mycelium-based composites have a TC of 0.044 W m^{-1} K^{-1}, which is on par with expanded polystyrene or even better. It is a desirable option for construction and transportation packaging applications due to its promising potential for use as mycelium composites.

Accounting for the greenhouse gas (GHG) emissions and environmental externalities linked to the building industry is becoming more and more popular. Wang et al. [131] used a life cycle assessment tool to analyze the consequences of an innovative aerogel building material derived from biomass on thermal comfort (TC:0.046-0.052 W m^{-1} K^{-1}) and to determine how much each stage contributed to the environmental load. It has been demonstrated that aerogel produced by freeze-drying raw materials derived from biomass is an environmentally sound and efficient alternative. More specifically, when compared to silica aerogel, the biomass-based aerogel using the freeze-drying method showed a reduction in potential impacts on climate change, nonrenewable energy, and terrestrial acidification by 76.20%, 92.76%, and 85.03%, respectively. The idea of economies of scale will allow for larger product batches and a continuous flow process, which will further improve the environmental performance of the product and process once the production and manufacturing process is significantly commercialized.

The synthetic insulations' thermal inertia is diminished, and their capacity to time-shift thermal waves and reduce temperature fluctuations within the building envelope is diminished, as they possess a lower density and a significantly higher thermal diffusivity compared to insulations derived from biomass. As a result, under dynamic ambient temperature changes and sun load conditions, biomass-based thermal insulations and their composites with mineral binders may perform better than the current synthetic insulations. Combined with the obvious environmental advantages of using biomaterials in construction, this provides enough incentive to investigate the thermomechanical properties of different kinds of biomass-based thermal insulation materials in more detail [132]. The thermomechanical characteristics of the *Miscanthus* × *giganteus* plant were investigated by Savic et al. [132] as a potential biomass source for thermal insulation intended to be used in outer wall panels. The received TC remained within the range of comparable bio-fiber insulation materials made of cellulose, with values between 0.08 and 0.10 W m^{-1} K^{-1}.

Novel thermal insulation materials for use in sustainable buildings were investigated by Rojas et al. [133] using agricultural residues (wheat straw and corn husk biomass). With a density of 10 kg m^{-3}, expanded polystyrene is directly comparable to other thermal insulation materials, while the TC value for corn husk (0.047 W m^{-1} K^{-1}) and wheat straw (0.046 W m^{-1} K^{-1}) was nearly identical. In order to improve energy efficiency and thermal comfort in homes, the fibers under study may be applied to create thermal insulation materials. According to the life cycle inventory analysis conducted for the manufacturing stages, the primary process to optimize the utilization of fibers available in agricultural regions is the drying of prototypes, which accounts for an average of 65% of total energy consumption. With wheat straw taking up 2 years and corn husk taking up 2.5 years, respectively, the embodied energy used in these materials for an average standard house would be recovered in less than 5 years of the lifespan of the building.

For a recently developed bio-based insulation material made with puffed rice grains, Khoukhi et al. [134] determined the most optimal production parameters, such as sample weight, temperature, and moisture ratio. In comparison to other insulating materials available for purchase like polystyrene, the newly developed material's lowest TC value (0.050 W m^{-1} K^{-1}) was found for the specimen weight of 16.5 g compressed to an 8-cm-diameter circular mold at a temperature of 263 °C and a moisture level of 16% under its natural state, devoid of any binders or additives. Because it is both environmentally friendly and has comparable thermal performance to other common insulation materials, puffed rice insulation material has a great deal of potential for commercialization.

The insulating properties of biomass-based insulation materials and aerated slurry-infiltrated mesh were studied by Almalkawi et al. [135]. Thermal analysis was used to identify the wall, roof, and floor insulation needed to meet the structure's loading and heating demands for the building. Aerated slurry-infiltrated mesh is the name of the structural material, which additionally has certain insulating properties. Alternatives to biomass-derived insulating materials used in this construction include ground wood (TC:0.052 W m^{-1} K^{-1}), shredded wheat straw (TC:0.038 W m^{-1} K^{-1}), and commercially available blow-in cellulose insulation (TC:0.039 W m^{-1} K^{-1}). In oven-dried conditions, it was discovered that ground wood with a particle size distribution primarily covering the 0.5–2.5 mm range and a bulk density of about 0.291 g cm^{-3}, as well as shredded straw with lengths less than 1.5 mm, provided viable levels of TC that were on par with those provided by commercially available cellulose insulation materials. Temperature increases were a feature of loose biomass-based insulation materials' TC; ground wood insulation had a less noticeable effect.

To enhance the wheat straw insulation materials' thermal properties and flame retardancy, Zou et al. [136] promoted efficient methods of partially carbonizing biomass and implementing fireproof inorganic cementing materials. Building safety and energy conservation were effectively safeguarded, as evidenced by the experimental results of TC of biomass-based insulation materials, which ranged from 0.061 to 0.096 W m^{-1} K^{-1}.

In order to produce thermal insulation panels and acoustic absorbers/sound insulation panels, Ouakarrouch et al. [137] developed and characterized novel environmentally friendly composite materials from abandoned natural fibers and cardboard waste. The low TC (0.065–0.1 W m^{-1} K^{-1}) of the composites made of 60% waste cardboard and 40% natural fibers is due to their increased air gap thickness, which promotes the absorption of low-frequency sounds. With the necessary thermal and acoustic insulation qualities for use in buildings, the new panels developed in this study represent excellent prospects for the development of local materials. These results clearly show the interest in replacing conventional insulating materials with these new composites, which have a fairly interesting thermal insulation capacity. This will undoubtedly guarantee the thermal and acoustic comfort of the building. Furthermore, it will contribute to the recycling of waste to reduce its harmful impact on the environment.

Water hyacinth petioles were investigated by Philip et al. [138] as a potential raw material source for panel boards based on agro-waste and water hyacinth that are intended to be used as thermal insulation. In comparison to conventional woods and other conventional materials like MDF, particleboard, plywood, and hardboard, the water hyacinth composite panel board demonstrated a lower TC value (TC:0.077 W m^{-1} K^{-1}), according to the testing results. The problems farmers encounter when they have to spend a considerable amount of money pulling invasive water hyacinth weeds can be resolved by using the plant as a thermal insulation material, improving sustainability in the building sector.

Using two different kinds of glue binders, Ramos et al. [139] evaluated the thermal behavior and environmental impact of two distinct corncob particleboards. Taking into account the values obtained for the thermal performance parameters (TC:0.046–0.097 W m^{-1} K^{-1}), the results showed that both types of corncob particleboards are viable options for environmentally friendly wall thermal insulation. In light of this, this research adds to our understanding of the scientific potential for the valorization of agricultural wastes and by-products as sustainable building materials.

A significant challenge as it relates to the circular economy framework and the green deal statement is the valuation of greasy wool into building components used in insulation. The creative and sustainable alternative applications for this livestock waste could reduce environmental issues and open up new opportunities for the expanding sheep farming industry [140]. As a creative and long-lasting substitute for throwing away low-quality wool from the area, turning raw wool into building applications also helps the environment by reducing pollution levels and opening up new opportunities for the expansion of the sheep farming industry. On the market, sheep wool insulation products in the form of 100% sheep wool soft mats (TC:0.032 W m^{-1} K^{-1}), rigid or semi-rigid panels made of sheep wool and polyester fibers (TC:0.040 W m^{-1} K^{-1}), and loose-fill fibers (TC:0.035 W m^{-1} K^{-1}) are already accessible.

Bicomponent fibers were used as a binder in the nonwoven materials that Rubino et al. [141] suggested using textile waste generated by an air-laying industrial production process. The most lightweight materials actually had a density of 68 kg m^{-3} and a TC of 0.040 W m^{-1} K^{-1}, whereas the heaviest materials had a density of 134 kg m^{-3} and a TC value of 0.050 W m^{-1} K^{-1}. The suggested materials might be suitably suggested to fill air gaps in masonry walls or as internal finishing, given the previously mentioned results and the acoustic and thermal insulating behavior seen after applying the materials to examples of walls. Moreover, one of the examined nonwovens in particular could serve as a valid resilient layer in a floating floor due to its damping properties, which are similar to those of conventional materials, and the positive behavior observed for a concrete floor.

Using sunflower straw that was abundant in the field and had a high cellulose content, Yang et al. [142] fabricated multifunctional thermal insulation materials with exceptional TC (0.047 W m^{-1} K^{-1}), superior superhydrophobicity, exceptional fire resistance, and high mechanical properties. These cutting-edge properties offer great potential for use in upcoming environmentally and energy-saving buildings and make it the perfect thermally insulating material for a variety of applications in challenging environments.

By combining recycled industrial (blast furnace slag and waste photovoltaic glass powder) and agroforestry (rice husk ash) wastes, Zhao et al. [143] prepared building insulation foam materials. When compared to conventional building insulation materials, the prepared specimens showed advantages in energy consumption and carbon footprint, reaching an optimal TC value of 0.050 W m^{-1} K^{-1}.

Veggie fibers' application in building materials is becoming more and more common due to their low carbon footprint and suitability as acoustic absorbers and hygrothermal panels. High-performance insulating panels made from vegetable fibers, such as straw fibers (TC:0.058 W m^{-1} K^{-1}) and olive tree pruning residues (TC:0.062 W m^{-1} K^{-1}), were the focus of an examination by Liuzzi et al. [144] concerning their hygrothermal and acoustical properties. Acoustically, both prepared panels demonstrated strong high-frequency absorption of sound, which was to be expected given the specimens' thickness. Vegetable fibers, such as straw and olive fibers, can be successfully used to produce indoor covering panels with hygrothermal and acoustic properties. This is an efficient substitute for the traditional material currently in use from an environmental standpoint.

The functionality of sustainable building walls composed of 80 kg m^{-3} (TC:0.039 W m^{-1} K^{-1}) and 100 kg m^{-3} (TC:0.039 W m^{-1} K^{-1}) straw bales were evaluated by Marques et al. [145]. It is possible to use straw bales as load-bearing walls or as an infill-insulating material within a timber structure. The findings demonstrate the need for appropriate coating materials to guarantee the straw bale solutions' ultimate effectiveness. Additionally, they provide evidence for the significance of coating materials to the dynamic behavior of straw bale wall solutions with respect to environmental moisture exchange and thermal delay. These findings also add to the building industry's growing confidence in the safe application of such unconventional building solutions. As a result, it will be possible to support the development of more environmentally friendly construction products using rice straw by fusing the advantages of natural materials for the environment with sound design and technical characterization, which are supported by standard testing guidelines.

The thermal and acoustic properties of oil palm wood binderless panels as insulators were studied by Mawardi et al. [146]. The lowest TC (0.050 W m^{-1} K^{-1}) and highest sound absorption coefficient (0.33) at 2000 Hz were found in panels containing large particles, according to the results. The oil palm wood binderless panel is a viable option for use as an insulating material in buildings, according to the findings. Furthermore, there are socio-economic and environmental benefits to be gained from the efficient use of oil palm wood.

Wet-dry, cool-heat, and freeze-thaw cycles were used by Wang et al. [147] to assess the durability performance of three different biomass-based geopolymer-based insulation materials like sawdust, rice husk, and wheat straw. Building thermal insulation based on biomass geopolymer materials is promising due to their low TC (sawdust geopolymer insulation material, e.g., has a TC of 0.089 W m^{-1} K^{-1}), acceptable compressive strength, good durability, and low energy consumption. Consequently, this study offers new perspectives in order to promote multifunctional insulation materials that simultaneously reduce heat transfer and noise sound, in addition to serving as a scientific reference for the development of test procedures and related standards for the durability of biomass insulation materials based on geopolymers.

With rice husk serving as the biomass-derived material, geopolymer acting as the binder, and hydrogen peroxide as the foaming agent, Wang et al. [148] conducted experimental research on a novel environmentally friendly bio-insulation. It was found that the TC drops from 0.095 to 0.082 W m^{-1} K^{-1} as the foaming agent/geopolymer mass ratio rises from 0.012 to 0.021. The rich resources of abandoned crops make this composite suitable for use in construction, particularly in rural areas. Building energy consumption and environmental pollution can be decreased simultaneously by converting straws and other biomass into thermal insulation. Furthermore, prefabricated buildings made of this composite material can serve as their core, thereby minimizing heat or cold loss and resulting in energy savings. In the area of building thermal insulation, it therefore has a promising future.

There are optimistic future expectations for environment-friendly biomass wastes in the field of construction and building industry and related fields of science. These alternative materials will contribute to the financial benefits as well as the development of materials from natural resources being a part of the green building initiative. However, there are still a number of visible features that need to be changed in the subject of natural biomass waste utilization. These characteristics requiring improvements are as follows: optimizing the design of building insulation materials; enhancing buildings' thermal insulation and energy usage of buildings; introducing novel energy-efficient processes; reducing the risk of negative effects (i.e., molding) caused by moisture and free water; moisture buffering; limiting greenhouse gas emission; reducing toxicity index of insulating materials; eliminating climate changes and impoverishment of resources; and lowering production costs, to name a few. Parallel to the advances mentioned above, other interesting applications for renewable wastes are expected, namely, in exterior protected construction, heat preservation, external and internal insulation, wall construction and heat insulation of cold storage, thermal and acoustic insulation of suspended floor constructions, partition board, ceiling coating, wall panel, light partition walls, floors, and roofing thermal insulation. However, commercialization is still the most challenging bottleneck for biomass waste–sderived insulation materials to be used as versatile materials.

5 Concluding remarks

Highlights and main findings of recent efforts on investigation and applications of natural biomass wastes derived from renewable resources which have been used as building insulation materials are compiled in this review. Sustainable biomass wastes, with well-designed thermal insulation properties, will not only bring many favorable features to building industry applications but will also provide a model system for developing and understanding the production of more sustainable insulating products. The use of more innovative and "greener" insulating materials may lead to improvement in energy conservation, reduction of the heat transfer coefficient, and improvement of the thermal resistance in insulating products (e.g., light partition walls, indoor doors and furniture, ceiling coating), as well as provides a more useful replacement for conventional building materials. With the aforementioned information in mind, it is possible to conclude that, as of right now, there is not a perfect thermal building insulation material which satisfies all the requirements regarding the most essential properties, such as TC, safety for the environment and human health, and affordability. The field has advanced technologically, so creating appropriate insulators that satisfy all needs requires more attention.

The use of biomass waste–derived insulation materials in construction materials allows for reducing the environmental ramifications of buildings not only during the maintenance of buildings (thermal comfort) but also allows the construction of more sustainable buildings. The commercialization of these materials and their use in new construction or renovations will help to achieve the European objectives of achieving economic net CO_2 emissions by the year 2050. The authors firmly believe that biomass waste–derived insulation materials deserve more research which can play a vital function for application in construction and buildings and can confer benefits on societies, the economy, and the whole environment in the future.

Author contributions PL: Writing (original draft), conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization.

MAG: Writing (review and editing), supervision.

Data availability All data and materials are in the manuscript.

Declarations

Ethical approval This declaration is not applicable.

Competing interests The authors declare no competing interests.

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