

Review

How Manufacturing Conditions Shape the Thermal, Physical, and Mechanical Properties of Bio-Based Insulation: A Review

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Abstract

The current need for thermal insulation building materials has led to the development of new materials and technologies, which are necessary to reduce carbon emissions. Lignocellulose materials are promising options for thermal insulation materials in construction, offering appropriate mechanical and environmental properties. While recent reviews focus primarily on material properties, a critical gap remains in the technical analysis of processing parameters and the comparative evaluation of alternative fabrication methods. This study provides a semi-systematic overview of manufacturing processes for lignocellulose-based thermal insulation, highlighting key production methods at the development stage: the most common hot pressing and compression molding, as well as less used hot drying, air-laid, wet-laid, needle-punching, and biological fabrication (mycelium-based). The results show that there is no single ideal method due to a fundamental trade-off: hot pressing provides superior mechanical strength, mycelium and needle-punching provide optimal thermal insulation, while room-temperature drying and blow-molding methods are the most environmentally friendly due to their minimal energy consumption. The key factors determining material performance are the material density, size, and type of raw material, which are strictly regulated by processing parameters.

Keywords: lignocellulosic biomass; hot pressing; compression molding; circular economy; waste valorization; sustainable building; thermal insulation; bio-based materials



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1. Introduction

The building sector is responsible for about 40% of carbon dioxide emissions [1]. According to the IEA [2], global floor area is projected to expand by 51% between 2023 and 2050, driving a 26.45% increase in material demand over the next six years alone [3]. At the same time, achieving carbon neutrality by 2050 [4] targets a building stock where at least half of the currently existing structures will still be operational. This dual challenge demands a two-sided approach: radically reducing the operational energy of existing buildings through deep renovation and strictly limiting the environmental impact of new constructions.

As buildings become highly energy-efficient or achieve net-zero operational status, the focus shifts from operational energy to embodied carbon (the emissions generated during the raw material extraction, processing, and manufacturing phases) [5]. Traditional market-leading thermal insulation poses a significant environmental barrier [6]. Fossil-fuel-based products, such as expanded polystyrene (EPS), have an unacceptably high carbon

footprint [7]. Even existing natural-based materials reduce their cyclicity and low-carbon benefits due to synthetic binders (PF, UF, MDI resins), especially for the dry processes. These resins require chemical synthesis, release formaldehyde and complicate disposal, thereby violating the principles of a cyclical economy [8].

Conventional insulation materials, such as mineral wool (stone and glass fiber) and synthetic polystyrene foams, currently dominate the market due to their cost-effectiveness and established popularity compared to bio-based alternatives [9,10]. Governmental regulation is required to prioritize the environmental aspects of insulation products over market self-regulation alone. The United Nations Environment Programme (UNEP) has proposed an “avoid-shift-improve” decarbonization strategy that involves avoiding raw material extraction through a circular economy, shifting toward renewable and low-carbon biomaterials, and improving efficiency by using steel and concrete only for essential needs [11].

Scientific interest in using bio-based materials as thermal insulation has intensified significantly since 2015 [12]. Studies show that natural materials in general possess higher thermal conductivity than commercial products, typically ranging from 0.03 to 0.1 W/(m·K) [13]; however, the combination of thermal, physical, and environmental properties has identified sheep wool and wood fiber as optimal alternatives to conventional insulators, such as rock wool and polystyrene [14]. Currently, straw and sheep wool represent the most extensively studied materials in the category of bio-insulation [15]. Modern production technologies for biological insulation materials show that their properties can be comparable to those of synthetic analogues. For example, in a study by Lafond and Blanchet [16], industrially manufactured wood fiber and hemp insulation boards produced by dry and wet methods with gas injection demonstrated a thermal conductivity of 0.036 W/mK at a density below 60 kg/m³. This corresponds to the range of values for expanded polystyrene. Agro-waste insulation materials have the lowest energy consumption during heating and cooling periods and have been shown to emit fewer polluting gases during production and operation [17].

Recent review papers (2024–2025) focused primarily on thermal, acoustic, mechanical and environmental properties, leaving the manufacturing process in the background. Existing reviews critically lack a technical analysis of processing parameters, an analysis of alternative technologies, a comparison of methods based on final material property criteria, and a critical evaluation and comparison of manufacturing methods [12,13,18–20]. Table 1 summarizes the recent review studies on bio-based thermal insulation, identifying key gaps and limitations that have been solved in the current review.

Table 1. Comparison of previous review articles and the current study on bio-based insulation materials regarding their research scope and identified limitations.

Entry	Material Source	Core Focus	Key Contribution	Notes	Ref.
1	Natural fibers; matrix—mineral, synthetic polymer; biodegradable binders	Physical parameters in fiber–matrix interactions; thermal, mechanical performance	Cattail-clay as optimal; alkali treatment benefits	No detailed specific production steps, parameters; the mycelial cultivation process is not considered as a complete production method	[21]
2	Agro and wood waste, mycelium-based; lavender distillation waste	Global research landscape; scientific trends in material properties	Exponential growth since 2010; France and China leading; thermal properties dominate over acoustic and fire-safety data	Lack of technical analysis, including material pretreatment, manufacturing pressure and bonding temperature	[12]

Table 1. *Cont.*

Entry	Material Source	Core Focus	Key Contribution	Notes	Ref.
3	Animal-, wood-, agricultural-based; mineral, synthetic, or bio-based binders	LCA; thermal benchmarking; standardized selection criteria vs. traditional materials	Cellulose, straw as carbon sinks, face thermal-energy trade-offs; sustainability is binder-type-dependent	Lack of detailed assessment of manufacturing parameters and how they influence the properties, fungal resistance, and fire safety of bio-composites	[13]
4	Wood fiber (rigid, flexible, loose-fill) vs. EPS and mineral wool	Material physical properties vs. system-level climatic performance via advanced predictive modeling	Competitive λ -values, superior moisture buffering, high thermal inertia vs. market barriers (cost, specialized labor)	No discussion on the wide range of other lignocellulosic materials (e.g., straw, hemp, agricultural waste, fungal mycelium, and wool); lack of detailed production process analysis	[22]
5	Bio-SIPs: cores (bio-foams, mycelium, rPET), facings (agri-waste/non-wood fibers), and eco-adhesives (plant oils/lignin)	Benchmarking manufacturing origins, physical performance, LCA	rPET and bio-PU lead in performance; hemp panels offer a viable OSB alternative. Mycelium moisture sensitivity and adhesive environmental footprint	Alternative processes (needle-punching and air-laid, wet process, hot drying) are not considered, no deep technical focus on the chemical/mechanical influencing parameters	[23]
6	Plant-, animal-based; agricultural waste; recycled synthetics (plastics, rubber, slag)	Thermal and acoustic performance against long-term durability, fire safety, and total embodied carbon	Sheep's wool and hemp comparable to EPS by thermal performance; low carbon footprint, require eco-friendly treatments	No detailed analysis of thermomechanical processing parameters, fiber pretreatment methods	[20]
7	Wood, plant fibers, agricultural by-products, recycled textile waste	Carbon storage capacity, thermal and acoustic efficiency, physical durability, predictive models	Superior carbon sequestration and acoustic performance but vulnerable to moisture and fire; specialized treatments and density-based predictive modeling are needed	No applied analysis of production processes; impact of specific fabrication methods on environmental impact and the possibility of mass implementation	[24]
8	Lignocellulose sources (wood fibers, agricultural waste, grasses, and non-wood plants)	Manufacturing processes, material pretreatment, and fabrication methods	Systematic categorization of 10+ fabrication methods and their influence on final material properties	Provides a technical explanation and the relationship between pretreatment, manufacturing parameters, binder type, density, thermal conductivity, mechanical strength, durability and industrial scalability	This study

This study focuses on fabrication methods and bridges the critical gap between materials science and real-world manufacturing. This approach introduces new insights into fabrication processes that will enable control over material structure. The investigation of production methods is essential for establishing the critical link between processing parameters and final performance characteristics, such as thermal conductivity, mechanical strength, moisture resistance, and also durability. A detailed review of pre-processing steps and forming methods is necessary to optimize material properties, provide a baseline for energy performance calculations, and conduct LCA (life cycle assessment). Current in-depth analysis of the process chain is justified by the urgent need to make natural insulation marketable.

This study answers the following central research question: what is the relationship between modern fabrication methods of lignocellulosic raw materials and the potential for creating multifunctional bio-insulation that combines low thermal conductivity with enhanced durability? By evaluating more than ten different production methods and their relationships, this review serves as a resource strategy for both academia and industry, identifying the most promising ways for expanding sustainable alternatives in construction worldwide.

2. Methodology

This study uses a semi-systematic (hybrid) review approach. Specifically, this review aims to comprehensively examine production methods for biodegradable insulation materials, summarize these technologies, and systematically assess how various processing parameters influence the final physical, thermal, and mechanical properties of the products.

The literature search was conducted using a systematic approach to identify relevant studies on bio-based insulation materials (Figure 1). Two primary academic databases, Scopus and Web of Science (WoS) Core Collection, were utilized to ensure comprehensive coverage of the field. The search focused on Title and Keywords using a multi-step query strategy. The following Boolean query was applied: ("lignocellulos*" OR "bio*" OR "natur*" OR "eco*") AND ("thermal insulat*" OR "building insulat*") AND ("material" OR "board" OR "panel"). This targeted approach allowed for the identification of studies where bio-based insulation is the primary focus of the research. The initial search yielded 3152 records from Scopus and 242 from Web of Science.

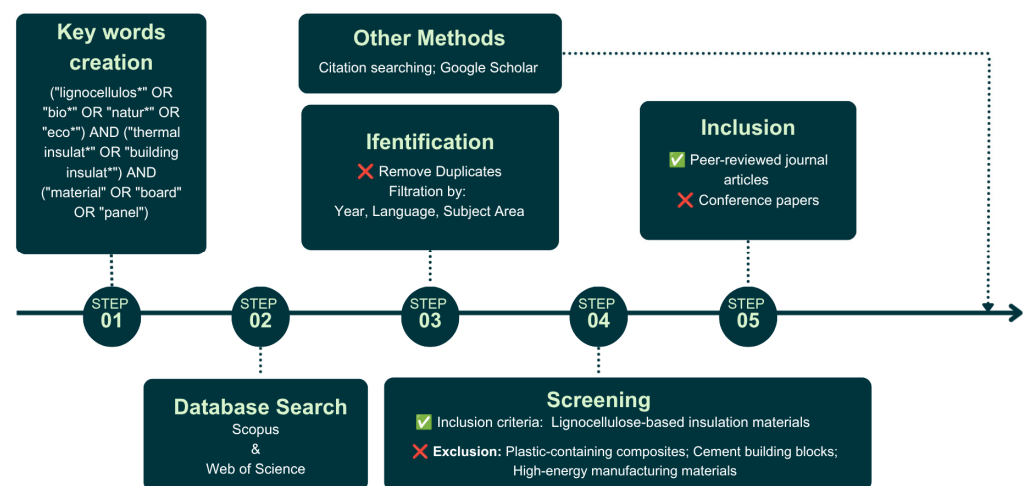


Figure 1. Flow diagram illustrating steps of the identification, screening, eligibility, and inclusion of studies on bio-based thermal insulation materials from the Scopus and Web of Science databases for the current review. The asterisk (*) serves as a truncation wildcard to capture word variations during the database search. In Steps 3 and 5, green checkmarks denote the applied inclusion criteria, while red crossmarks signify the exclusion criteria.

The datasets were polished based on the following inclusion and exclusion criteria by (1) document type: only original research articles were retained; retracted works, conference reviews, and proceedings papers were excluded; (2) a language filter was applied for English only, and (3) the timeframe was restricted to 2006–2026 to capture modern industrial trends; (4) records belonging to irrelevant subject areas (e.g., Medicine, Arts and Humanities, or Social Sciences) were excluded, focusing on Engineering, Materials Science, Environmental Science, and Energy. Duplicate removal and preliminary bibliographic data processing were performed using the bibliometrix package for the R programming language [25].

After removing duplicates and applying the initial filters, 3204 records remained for the screening stage. These records were uploaded to the Rayyan web-based platform [26] for a rigorous title and abstract screening. During the screening process, studies were excluded if they did not directly address building materials or thermal insulation applications. Specific exclusion criteria were applied to remove articles focusing on plastic-dominated composites, traditional cement-based building blocks, or materials

with high embodied energy that fell outside the “bio-based” scope. This stage resulted in a narrowed pool of 62 articles.

To ensure the technical depth of the review, particularly regarding the analysis of production methods and their influence on material properties, a secondary search strategy was employed. This involved manual searching via Google Scholar, backward and forward citation tracking (snowballing), and following specific journal recommendations. To minimize selection bias during the secondary search (Google Scholar and snowball sampling), all retrieved articles were filtered using the same inclusion criteria and database indexing checks as Scopus/WoS records. Furthermore, bias was eliminated through a rigorous technical quality check, excluding any studies that lacked an accurate description of the manufacturing process. These additional methods helped identify key papers that might have been missed by the initial database queries due to highly specialized terminology. After a final full-text eligibility assessment and technical quality check, 50 articles were selected for final inclusion and detailed analysis.

The final selection of 50 articles was systematically categorized to provide clarity on the different fabrication techniques and their impact on final material performance. To handle the wide range of presented indicators, the extracted variables were classified into three main categories: 1. Material processing and structure: type of raw material, fiber/particle size, binder content, manufacturing conditions (temperature, pressure), density; 2. Thermal and mechanical properties: thermal conductivity (λ), compressive/flexural strength, internal bond (IB); 3. Hydraulic and stability properties: water absorption and thickness swelling (after 2 h, 24 h, etc.) and thermal stability.

3. Results and Discussion

3.1. Raw Materials

The differentiation of thermal insulation in the literature is determined by its origin: animal, plant, mycelium-based, mineral thermal insulation and categorized as organic fibrous materials [27–29]. A variety of lignocellulosic sources utilized for bio-based insulation production reviewed in this study are shown in Figure 2.

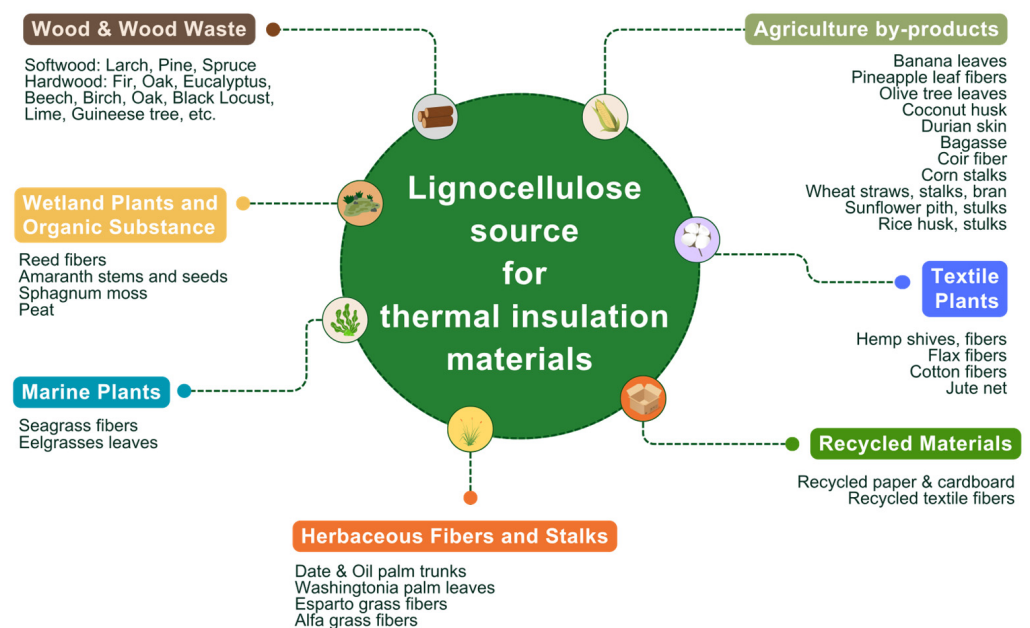


Figure 2. Classification of lignocellulosic sources for the bio-based thermal insulation materials development.

A co-occurrence analysis shows that agricultural and wood waste are the most frequently used raw materials in production cycles in recent studies due to their huge abundance, low cost, and rich structural composition (cellulose, hemicellulose, and lignin), which makes them ideal for producing high-value, sustainable materials and energy (Figure 3). Utilizing waste, for example tree bark, highlights a highly sustainable availability vector, as it exists as a direct by-product of timber debarking processes, yielding approximately 80 kg of wet bark per 1 m³ of processed roundwood [30]. Beyond its volume availability, integrating bark into insulation panels effectively resists mechanical stress while simultaneously reducing hazardous indoor formaldehyde emissions compared to conventional synthetic or standard wood-based panels [31,32].



Figure 3. Co-occurrence heatmap of biomass types and their combinations in bio-based thermal insulation material studies. The numbers inside the cubes represent the frequency (the exact count) of how many times a specific raw material was used with a specific production method in the dataset.

Currently, there is a clear trend toward developing hybrid compositions, such as combining recycled paper and textile fibers with natural plant-based raw materials [33]. Despite the variety of these combinations, the dominant research approach remains the use of materials within the same morphological groups, as this enables achieving stable performance characteristics. However, the thermal performance of complex organic composites, such as a mixture of hemp husk, sheep wool and lime (0.074 W/mK) [34] or a combination of sunflower and wheat stalks with vermiculite (from 0.063 to 0.334 W/mK) [35], remains higher than that of synthetic non-renewable insulation types.

Different raw materials reach their lowest thermal conductivity (λ) at slightly different “critical” densities due to their inherent cellular structure, microporosity, and fiber diameter: wheat straw and reed at densities around 60 kg/m³; hemp and flax at the range of 60 to 85 kg/m³; wood fiber (softwood) requires higher densities to ensure structural integrity, and optimal ranges are typically between 100 and 150 kg/m³, where $\lambda = 0.038$ – 0.045 W/mK is achieved; for cellulose (loose filler), the optimal density values are from 30 to 60 kg/m³ [36].

3.1.1. Morphology Role in Bio-Based Thermal Insulation Production

The internal and external structure of the plant (morphology) determines the form and structural category of the biomass. Six main types are used in the production of thermal insulation, as shown in Figure 4.

Fibrous raw material forms (red in Figure 5) are predominantly used in textile-type methods (air-laid, needle-punching or wet-laid). Particulate (blue in Figure 5) and powder (green in Figure 5) forms require bonding processes or pressing to achieve structural integrity. At the same time, there is no difference ($p = 0.360$) in thermal conductivity only due to the material’s form (Figure 6). Thermal conductivity in bio-insulation is governed by three primary factors: moisture content (hygrothermal behavior), density and porosity, and fiber orientation (microstructure) [24,37,38]. Through the production methods, the

internal structure of the material is formed, which ensures a certain density, which will be discussed in the following paragraphs below.



Figure 4. Structural forms and morphology of plant-based materials used in bio-based thermal insulation materials.

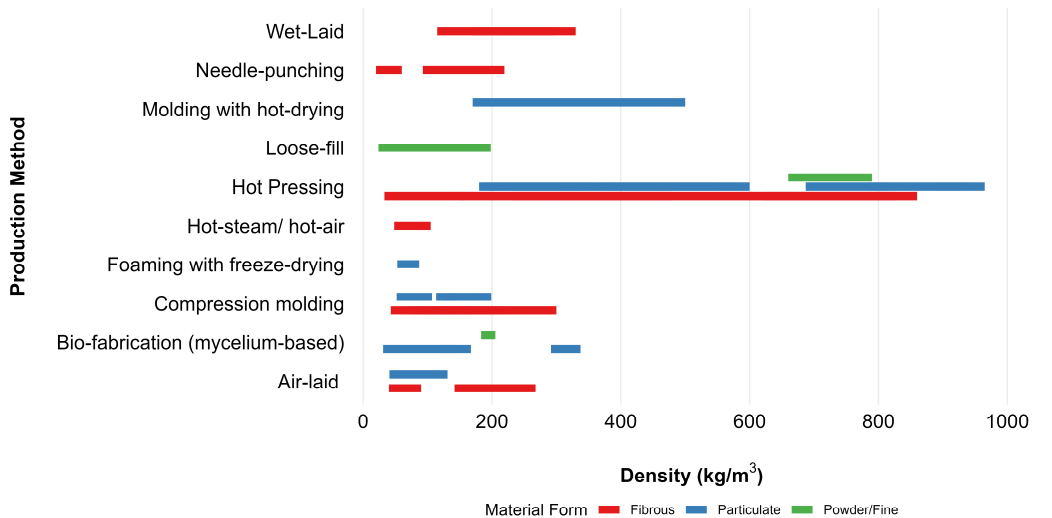


Figure 5. Density ranges of lignocellulose-based insulating materials depending on the production method and the form of the raw material (fibrous, particles, powder).

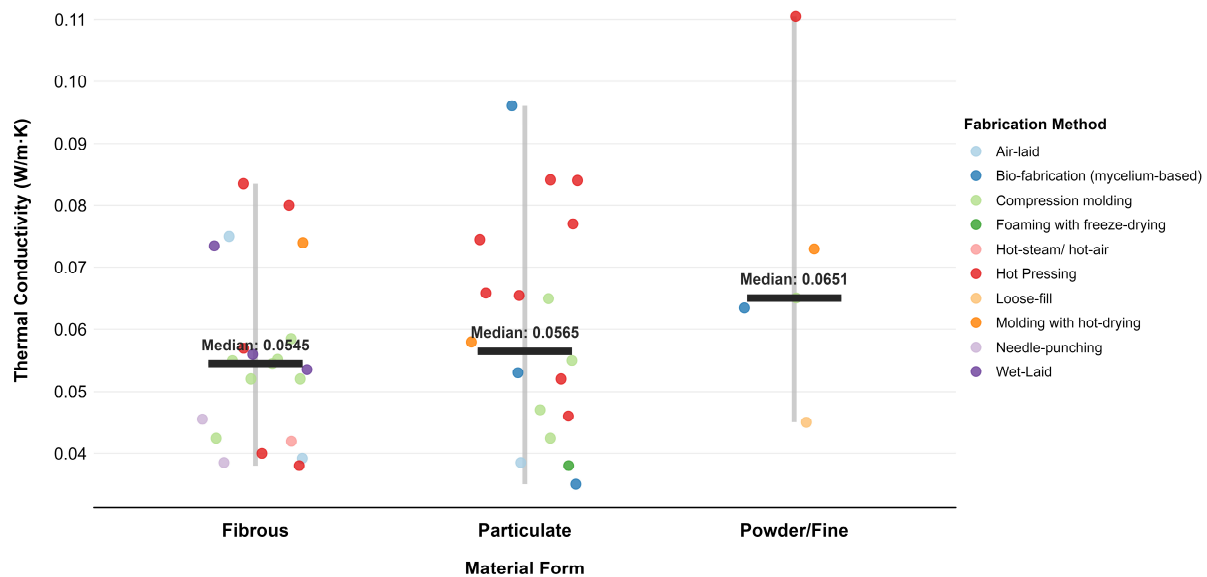


Figure 6. Distribution of thermal conductivity across different raw material forms (fibrous, particulate and powder) and processing techniques with layered group medians.

3.1.2. Size Role in Bio-Based Thermal Insulation Production

The geometric characteristics of bio-based particles determine the density, porosity, and thermal properties of the final material. A high proportion of fine hemp particles (0–5 mm) increases the mechanical strength and sorption capacity of panels by increasing the specific surface area and improving compaction [39]. At the same time, removing particles smaller than 0.5 mm during the production of wood fiberboards is not economically viable [40].

Larger palm [41] and amaranth (4 mm) particles [42] provide the best thermal insulation performance. Larger particle sizes reduce the compactness of the structure, and since thermal conductivity is directly related to material density, less dense panels exhibit lower thermal conductivity [43]. However, if particles are too big, it creates larger air-filled voids, which allows heat to transfer more efficiently, increasing thermal conductivity.

To achieve specific raw material size, sorting and sieving are used as a preparation step, but some techniques use the whole corn cobs [44] or leaves [45]. The separation is important because different anatomical parts of a plant show different thermal conductivities, which can influence final properties [42].

Figure 7 illustrates the dimensional ranges of various raw materials used in bio-based production, categorized by their source group. Many groups share similar dimensions from 1 mm to 10 mm. The agro-waste (yellow) group shows the highest variability: wheat straw and corn cobs are used in the largest dimensions (up to ~300 mm), while oil palm trunks are processed into much smaller particles (mostly between 0.1 and 1 mm).

The length of the fibers have a significant effect on the mechanical and thermal properties of the material. Fiber length determines how well the fibers interlock to trap air, directly influencing heat transfer through the product [40]. Short fibers tightly pack into voids, increasing the material's density. This improves mechanical strength and workability but can increase heat transfer because there are fewer trapped air pockets. Long fibers create a complex, high-porosity matrix that traps larger amounts of air [46]. This significantly lowers thermal conductivity and creates a better thermal barrier, but it decreases mechanical bonding/strength [47].

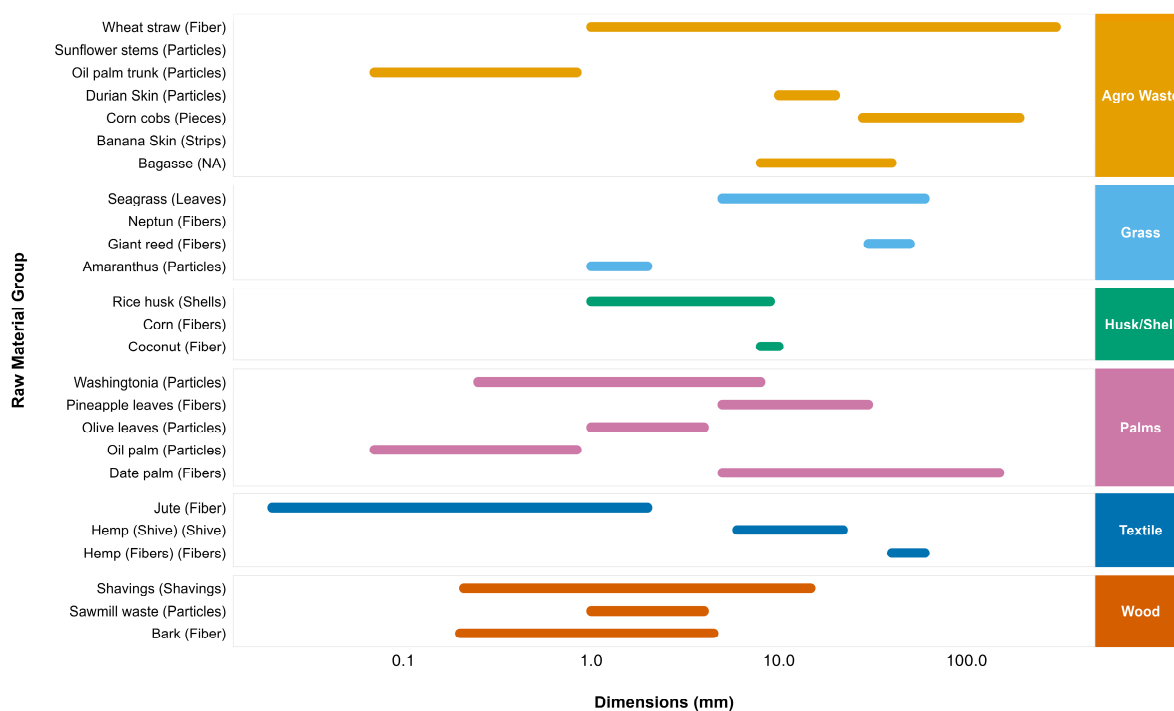


Figure 7. Comprehensive overview of the raw material dimensions used for panel fabrication across various lignocellulosic raw material categories.

Understanding the type of raw material and the typical size ranges utilized in the studies focusing on bio-based thermal insulation building materials is important for predicting the functional behavior of specific biomass types during both processing and application.

3.1.3. Chemical Composition

A primary concern of bio-based thermal insulation is its hydroscopic nature, which is determined by the chemical properties of lignocellulose materials [48].

The chemical composition of plant biomass is not static; it is a dynamic system shaped by the interaction of genetic, environmental, and developmental factors, which can lead to process instability and the homogeneity of the natural material [49,50].

Plant-based raw materials are natural composites of cellulose, hemicellulose, and lignin, whose structural integrity plays a central role in the functionality of bio-based materials. Table 2 summarizes the main components of biomass, with their characteristics and role in bio-thermal insulation materials.

Table 2. Summary of lignocellulose biomass components.

Component	Main Role	Characteristics	Ref.
Cellulose	Provides rigidity, strength, and thermal stability. Chemical treatment increases crystallinity to 60.9–64.9%. Larger particles (600–849 μm) maintain higher crystallinity because heavy grinding damages the crystal structure.	Primary structural component. Ranges from 37 to 64% in wood waste (pine, eucalyptus) and up to 80% in hemp fibers. Agricultural residues contain 33–50%.	[51–56]
Hemicellulose	Interacts with cellulose and lignin to maintain biomass integrity. It is highly hygroscopic, significantly affecting the thermal and mechanical properties of insulating materials.	Branched polysaccharide, smaller in mass than cellulose. Reaches up to 32% in agricultural residues (giant reed, rice husk).	[55–57]

Table 2. *Cont.*

Component	Main Role	Characteristics	Ref.
Extractives	Influence thermal conductivity. Hydrophobic extractives (e.g., from birch bark) improve water resistance and durability of insulation foams without degrading thermal performance.	Composition varies by species, directly impacting pressing and bonding parameters during manufacturing.	[58]
Lignin	Key determinant of processing conditions; high levels alter the required binding agents and manufacturing settings.	High in wood waste (26–34%), intermediate in agricultural residues (7–25%), and low in plant fibers like hemp (below 11%).	[52–56]

3.1.4. Environmental Impact

Plant-based insulation materials improve sustainability by significantly reducing carbon emissions during production. They actively absorb CO₂ during growth and require less energy to process. This makes their overall carbon footprint much smaller than that of traditional fossil-fuel-based alternatives [24].

Among renewable materials, cellulose and hemp have proven to be the most environmentally friendly (although they are damaged by chemical additives); however, not all “green” materials are created equal [59]. Some processes around bio-mass cultivation or producing lead to a potentially negative environmental impact. For example, cultivating agricultural crops for biomass requires fertilizers, manure, and land clearing. Nitrogen and phosphorus runoff from these fertilizers can cause severe eutrophication (algal blooms in aquatic ecosystems) and acidification in soils. Producing bio-based materials demands significant arable land and irrigation. Land-use changes, such as converting natural forests or grasslands into cropland, can drastically increase water stress and biodiversity loss, sometimes even releasing more carbon than the biomaterial saves [60].

The chemical conversion of biomass into usable materials (e.g., extracting biopolymers or natural fibers) can be highly energy-intensive. If the energy grid relies on fossil fuels, processing and freeze-drying can negate the original climate benefits [61].

The use of a demountable design strategy further reduces the environmental impact by 10–50% [62]. At the end of their life cycle, the insulation panels can be disposed of using pyrolysis, which produces useful products such as bio-char and bio-oil. However, this approach requires upgrading the production processes, especially when using slow pyrolysis at 550 °C or steam pyrogasification at 880 °C [63].

The energy costs of building operation also affect the environmental friendliness of a material. Synthetic materials are good insulators with low thermal conductivity; however, their production is energy-intensive and environmentally harmful. Moreover, they are often vapor-impermeable, which can trap moisture and degrade a building’s energy performance over time [64]. At the same time, to provide sufficient resistance (U-value), which is a more comprehensive indicator for evaluating efficiency than thermal conductivity alone, natural materials require a greater thickness [65]. Consuming a larger amount of raw materials also potentially leads to a reduction in environmental friendliness.

3.2. Comparative Analysis of Pretreatment Methods

To overcome the natural limitations of raw biomass, such as amorphous structure and hydrophilicity, various pretreatment methods, named also as fiber modification or fiber activation [66], are used. Pretreatment modifies the fiber surface to improve interfacial adhesion between the fibers and the matrix [67]. Since the amorphous regions of the original fibers are highly hydrophilic, water absorption increases, which negatively affects

the performance of natural thermal insulation materials. For a comprehensive overview, in Table 3, pretreatment methods used for bio-based thermal insulation materials are grouped, summarizing the pretreatment parameters, microstructural modifications, and resulting material properties.

Table 3. Summary of pretreatment methods of lignocellulose biomass for thermal insulation materials production.

Pretreatment Type	Raw Materials	Key Operational Parameters	Microstructural Impact	Resulting Properties	Ref.
Mechanical	Hardwoods, softwoods, corn stalk, wheat straw, reed, Giant reed, tropical wood shavings	Twin-screw extrusion (water–solid ratio 4:1); single-disc refiner (1450 rpm, 20 °C); defibrator (3000 rpm, 155 °C, 550 kPa); ball/impact milling (2000 rpm)	Structural definition (separating cell bundles from single cells); preservation of chemical components compared to chemical routes	50% increase in flexural strength; reduced the material's affinity for water; decreased mold growth; increased density; slow down moisture kinetics	[42,68–72]
Hydrothermal	Eucalyptus, rice straw, <i>Cynara cardunculus</i>	Steam explosion, hot water extraction, hydrothermolysis Temperature: 60–215 °C Pressure: up to 1.5 MPa Duration: 3 min to 8 h	Lignin condensation; destruction of β -O-4' and ether bonds; sub-product degradation (e.g., 5-hydroxymethylfurfural); breaking of hydrogen bonds	Increase internal bond; improved water resistance; higher density; increased bending strength and stiffness; decreased thickness swelling and water absorption	[73–76]
Chemical	Alfa grass, hemp, wood chips, <i>Posidonia oceanica</i> , Esparto grass, banyan bark, banana leaves	2–10% NaOH, 2% Acetic acid, or 3.5% NaCl Temperature: Room temp. to 120 °C Duration: From 2 h to overnight boiling	Removal of amorphous phases (lignin, hemicellulose); increased global crystallinity; enhanced surface roughness; removal of waxes	Improved thermal stability, tensile strength; fiber–matrix bonding capability	[43,67,69,77–79]

The criteria for selecting a pretreatment method are based on the energy demand of the process, preserving the lignocellulosic fraction, minimizing degradation products, and using inexpensive chemicals [80].

Also, not all pretreatment methods may be suitable for a specific material. The fiber composition of lignocellulose materials directly determines the choice of pretreatment method because different plant species and material types (wood vs. agricultural waste) have varying ratios of cellulose, hemicellulose, and lignin [81].

The purpose of mechanical fiber processing is to separate biomass fibers and increase the surface area [69]. During mechanical processing, a certain fiber size is formed, so the milling process should be optimized to get a proper fiber size, which determines the self-bonding and cohesion of fibers [72]. The choice of processing method will affect the final properties of the material, as short fibers generally pack together more tightly, which increases the apparent density of the composite and decreases its porosity. Because still air trapped within pores is a poor conductor of heat, reducing porosity increases thermal conductivity [82]. Too big particles increase thermal conductivity and require additional cycles of the milling run, which can lead to an increase in the process time [71].

Hydrothermal pretreatment modifies lignocellulosic biomass by breaking down hemicellulose and partially depolymerizing lignin. The advantage of this method is that no chemical components are used during this treatment, and at high temperatures, hemicellulose and cellulose breakdown products are formed (5-hydroxymethylfurfural), which, during the following hot pressing, act as a natural glue [75]. At the same time, the long duration of the process at high temperatures requires intensive energy inputs and produces a wastewater stream rich in organic pollutants. The temperature presented in the literature ranges from 60 °C to 215 °C for various types of natural fibers: softwoods, hardwoods, and non woody fibers. Treatment durations can be from 3 min to 6 h [74].

Chemical pretreatment differs from mechanical and hydrothermal pretreatment in that it involves the use of reagents (acids, alkalis) to break down the rigid natural bonds between cellulose, hemicellulose, and lignin [67]. The use of chemicals is a major impact on the environment, as well as water consumption and by-product disposal. Using alkaline solution to reduce emissions at a lower concentration (2% at room temperature for 24 h) can remove oils, waxes and contaminants from banana leaves and increase surface roughness, but lignin is not completely removed under these conditions [78]. To more effectively separate fibers and remove amorphous compounds from the fiber surface, chemical treatment is carried out at a high temperature of 60 °C for 24 h [70,73]. A combination of thermomechanical treatment with a steam explosion and alkali (4% NaOH) pretreatment improves the antifungal properties of the material, as it depletes the nutrients needed for mold growth [68].

3.3. Bonding

The choice of binder has a multifaceted impact on the physical, thermal, and biological properties of bio-based insulation materials. The primary role of a binder is to bridge the gap between distinct components (e.g., natural fibers or agricultural waste) [83]. Increasing the binder content (e.g., synthetic polymers such as PVA or styrene-acrylic acid) from 13% to 40% fills the voids between the biomass fibers. This densification creates a harder matrix that improves mechanical strength, structural integrity, and thermal stability but reduces the material's insulating properties due to porosity reduction [84,85].

The chemical composition of the binder determines the hygrothermal and biological properties of the board. Polysaccharide-based binders (starch and dextran) act not only as mechanical adhesives but also as active moisture-regulating components, improving the moisture-buffering capacity (MBV) of the composite. However, the organic origin of the binder negatively affects the material's biological resistance, providing a substrate for microbial growth under high-humidity environments (>80%) [39,86]. Table 4 summarizes the binders used during bio-based insulation, highlighting advantages, critical challenges and process conditions.

Table 4. Summary of binders used for the production of thermal insulation materials and their characteristics.

Binder Classification/Examples	Manufacturing Process and Conditions	Key Advantages	Critical Challenges and Material Trade-Offs	Ref.
Synthetic (MUF, UF, pMDI)	Hot pressing	High density; mechanical strength and stiffness	Formaldehyde emissions; increases thermal conductivity; environmental effect	[87,88]
Polysaccharide-based (Starch, dextran, cellulose derivatives)	Ambient-temperature/cold-pressing, layering, soaking	Hygrothermal functionality; Moisture Buffer Value (MBV); low energy consumption; natural-based	Susceptibility to microbial growth; structural integrity and stress transfer between fibers	[39,85,86,89]
Water-based polymers (PVA, styrene-acrylic copolymers)	Pressing at ambient temperature	Low energy consumption; thermal stability	Densification leading to reduced porosity and higher thermal conductivity	[84,85]
Organic Acids (Citric acid + glycerol)	Hot pressing	Effective cross-linking; increases IB	Reduces tensile strength; energy consumption; risk of thermal degradation/charring of biomass	[41,90]
Protein and marine-based (Casein/lean curd, chitosan, sodium alginate, amaranth)	Dissolution in mild acids/water at room temperature (25 °C), mechanical stirring	Eco-friendly matrices; effective utilization	Moisture sensitivity; vulnerability to decay; ethical concerns regarding food vs material resource competition; chemical processing required for chitosan stabilization offsets environmental benefits	[42,89,91,92]
Binderless (Self-bonding)	Grain expansion, wet-laid processes, hot pressing	Mechanical properties, no toxic emissions; no chemicals used	High fluctuation in mechanical properties depending on biomass homogeneity and process parameters	[93,94]

For rigid semi-structural insulation panels, where structural load transfer and high internal cohesion are required, binderless (self-adhesive) hot pressing or biochemical cross-linking (citric acid) is suitable. The binderless method of thermal insulation material production is a sustainable alternative, with the advantage of eliminating formaldehyde emissions without significantly reducing stiffness. Figure 8 presents a comparison of internal bond (IB) strengths for various binder types and manufacturing methods for biodegradable insulation materials. However, a limited number of methods were analyzed due to the lack of research data on internal bonding; most were related to the hot-pressing method production. As shown in Figure 8, binder-free boards produced by hot pressing show competitive IB (internal bonding) values ranging from 0.2 MPa to over 1.2 MPa, which corresponds to the standard for internal bond strength for non-load-bearing fiberboards. For the binderless panels made of *Eucalyptus grandis*, the more severe the processing conditions (higher temperature or longer time), the higher the internal bond value. Fiberboards processed at 150 °C for 8 h demonstrated a strength of approximately 0.5 MPa [74]. Internal bonding values of 0.07–0.02 Mpa are demonstrated in softwood tree bark panels produced with wet-laid technology; however, due to the lack of binding resins, the tensile strength of the boards is very low (especially for boards with long fibers of 7 mm), which limits their structural use [93].

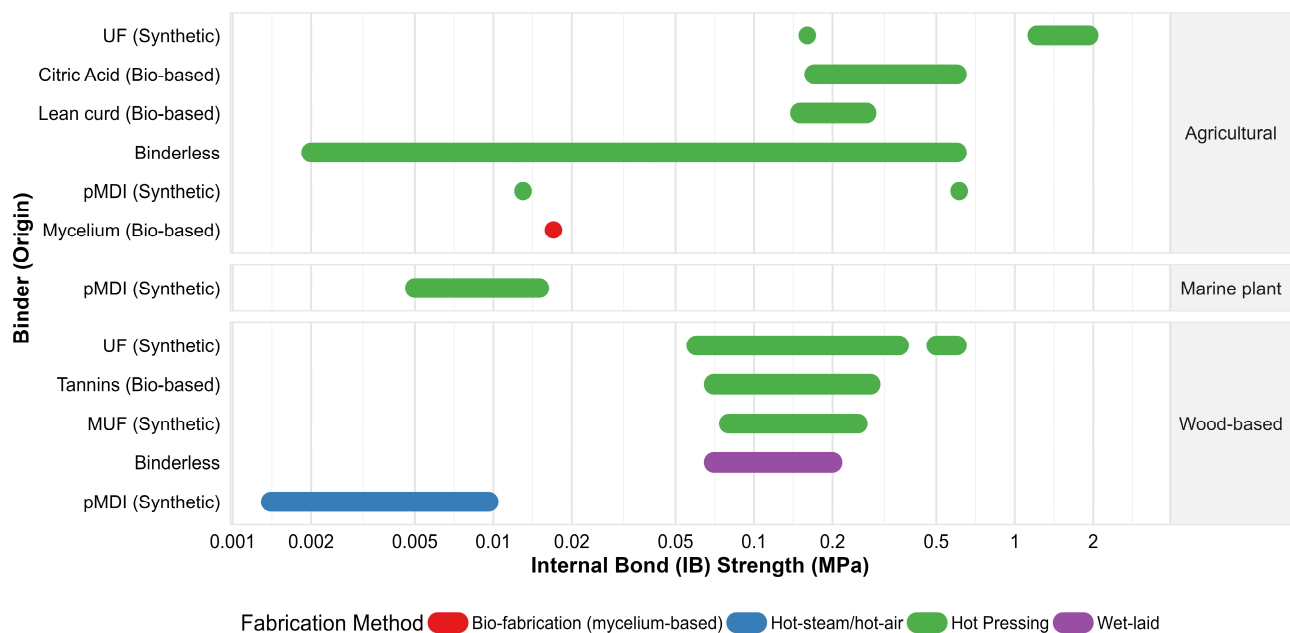


Figure 8. Comparison of internal bond (IB) strength across different binder types and fabrication methods for bio-based insulation materials.

The bond strength depends on the particle size and the target density of the boards [91]. In the case of citric acid, particle size influenced bonding, as the smaller the particles, the greater their total surface area and the stronger the ester bonds formed per unit volume [41]. In the case of tannins, if the target board density was low (less than 300 kg/m³), the bark particles were poorly pressed together in the press, leaving numerous voids, and even the highest-quality Mimosa tannin could not form a strong adhesive bond. As density (compression) increased, the bond strength increased linearly [95].

In terms of thermal conductivity, synthetic, biodegradable, and binder-free panels show similar behavior with increasing density (Figure 9). As density increases, bio-based panels (like wood fiber or hemp) can hold more capillary water, leading to higher thermal conductivity. Bio-based binders are highly hygroscopic; for example, lean curd retains more moisture from the air than classic panels [91]. Such a combination accelerates moisture

absorption ability, which leads to a rapid increase in the thermal conductivity coefficient. This combination accelerates moisture absorption, resulting in a rapid increase in thermal conductivity for bio-insulation panels with bio-binders. In this regard, using synthetic binders in bio-based insulation panels is more beneficial, as it improves their moisture behavior by reducing breathability and lowering the material's moisture buffering capacity, protecting the organic fibers from fungal growth and structural degradation [96]. Mold is a critical construction problem with bio-based materials because of their organic composition and hygroscopic nature. Due to the organic composition and high moisture absorption, wood-based materials are a perfect environment for fungi. The combination of *Posidonia* (or rice straw or husk) and sodium alginate proved to be the least susceptible to decay in a humid environment when used with a bio-based binder, which significantly extended the life of the material compared to xanthan gum or gum Arabic [18].

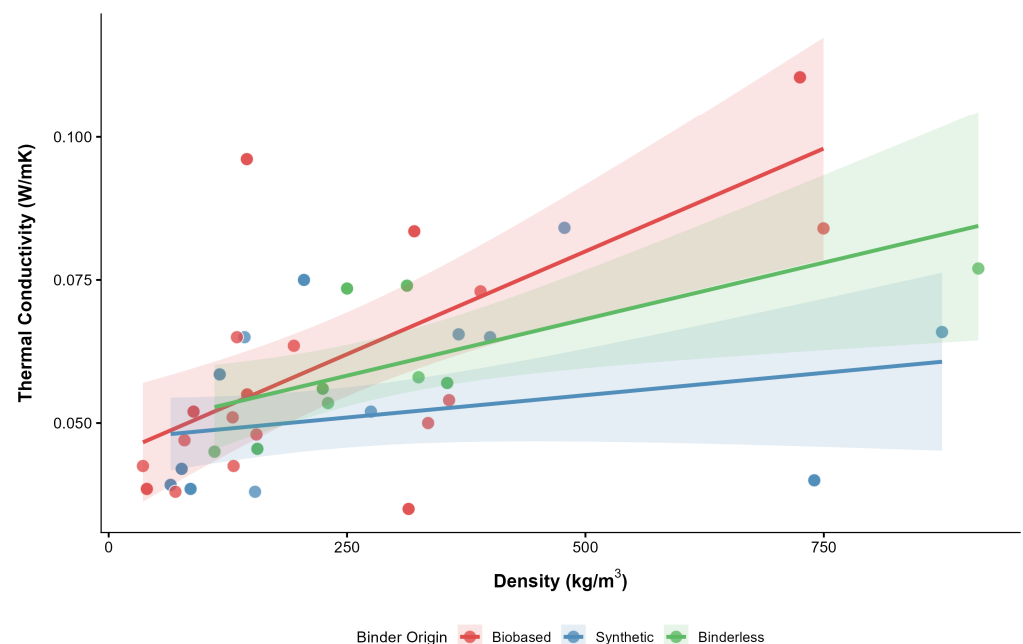


Figure 9. Scatter plot with regression lines of thermal conductivity versus density for different binder origins.

The development of bio-insulation is characterized by a critical trade-off where ecological purity often compromises durability, processing efficiency, and cost. When considering the impact of additives on the product lifecycle and its environmental properties, fossil-based (synthetic) additives and binders significantly degrade the overall lifecycle analysis of biomaterials, even if their share is small. This impact manifests itself both during panel production and disposal. For example, a polyester binder containing only 15% of the hemp insulation's mass has a lower environmental impact than growing flax alone [97]. At the same time, transitioning to carbon-neutral alternatives, like starch or casein [91], introduces major technical and financial liabilities. Their high moisture sensitivity demands mandatory, costly integration of natural antifungal treatments to prevent early biodegradation [89], which increases the final material cost [98].

3.4. Manufacturing Methods

Depending on application and form, bio-based thermal insulation can be flexible, rigid, loose, internal or external and applied to roofs, floors and walls [99]. Thermal insulation material type is determined by the processes and techniques used in their manufacturing. Liu et al. [100] categorized manufacturing methods of bio-based insulation

materials as bonding, molding, natural form, pressing, hot pressing, injection molding, foaming, and others. Lu et al. [13] additionally mentioned freeze-drying and needle-punching. Over time, hot pressing and compression molding remain the most frequently used techniques for manufacturing rigid and semi-rigid bio-insulation boards (e.g., from hemp, bamboo, flax, or agricultural waste). Bio-insulation must have a low density (to trap air) but sufficient mechanical strength to be handled and installed. Compression molding allows manufacturers to adjust the board's density and thickness by controlling the applied pressure [71,101,102]. For more effective bonding, which is necessary to ensure structural properties, to connect the fibers and to activate the binder, increased temperature and pressure are required (hot pressing) [84,95,103,104].

The production processes for the reviewed bio-based thermal insulation materials can be divided into four principal stages (Figure 10).

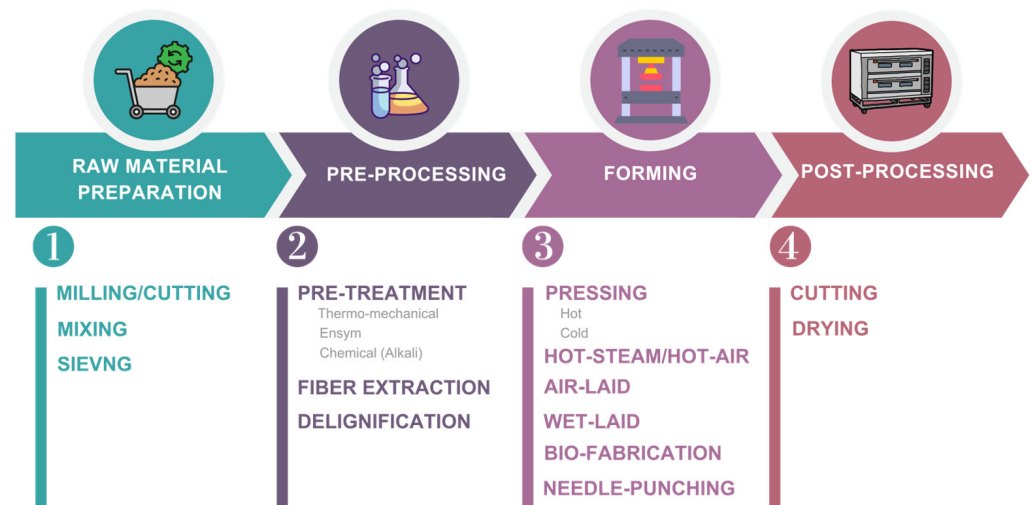


Figure 10. Lignocellulose-based thermal insulation manufacturing processes overview. The stages are presented in sequence; some of them can sometimes be skipped. The figure describes the production in the development or design phase of bio-based thermal insulation panel development.

The technological matrix of the pre-fabrication step for different production methods (Table 5) serves as a potential indicator of its environmental footprint and embodied energy. While the final product is considered sustainable, the heavy thermal and electrical inputs required to process, clean up, or stabilize bio-based materials can significantly offset their natural “green” advantages [105].

Table 5. Technological stage matrix for raw material pre-fabrication step. Background color-coding indicates processing requirements and potential energy consumption: pink highlights mandatory steps (“Yes”), green indicates steps not required (“No”), and yellow represents variable options (“No/Yes”) depending on the manufacturing process.

Fabrication Method	Raw Material Pre-Fabrication			
	Washing	Cutting	Drying	Sterilization
Air-laid	● No/● Yes	● Yes	● Yes	● No
Biological fabrication	● No	● No/● Yes	● No/● Yes	● Yes
Blowing technique	● No	● No	● No	● No
Compression molding	● No/● Yes	● No/● Yes	● No/● Yes	● No

Table 5. Cont.

Fabrication Method	Raw Material Pre-Fabrication			
	Washing	Cutting	Drying	Sterilization
Foaming and freeze-drying	● No	● No	● Yes	● No
Hot Pressing	● No/● Yes	● No/● Yes	● No/● Yes	● No
Hot-steam/hot-air	● No	● Yes	● No	● No
Molding with hot drying	● No	● Yes	● No/● Yes	● No
Needle-punching	● Yes	● No/● Yes	● No	● No
Wet fabrication	● No/● Yes	● Yes	● No/● Yes	● No

Washing requires massive volumes of water for cleaning dirt and contaminants from raw materials (or cleaning equipment between batches). The environmental load stems from the electricity needed for water pumping and heating, as well as the pollution potential of chemical detergents if not bio-based [106]. In wet-laid technology, water is the main component, serving not only as a binder but also as a medium for the release of fibers during defibration [107–109]. The water must be recycled, reducing the concentration of substances extracted from the materials, potentially requiring the addition of chemical reagents such as defoamers.

The impact on energy demand of physical size reduction (e.g., chipping biomass, cutting, milling, grinding) is relatively low unless the equipment runs inefficiently, which generates frictional heat and wasted energy [110].

Drying [71] requires significant thermal input to remove moisture or neutralize biological activity. Evaporating moisture typically requires between 1.5 and 2.5 kWh of thermal energy per kilogram of water removed. Total manufacturing embodied energy typically ranges from 2 to 8 kWh/kg of finished insulation panel [111].

Foaming and freeze-drying [77] is the most energy-intensive stage, requiring a load that needs to drive the condensers, vacuum pumps, and sublimation heat.

Hot pressing and compression molding are characterized by intense heating above 75 °C. Although molding and hot drying [112] reach temperatures of 200 °C during the main fabrication stage, pre-drying is also needed.

Based on the pre-processing matrix shown in Table 5, the blowing technique is highlighted as the most potentially “green” option in terms of pre-processing; however, this type of insulation is not suitable for an open ceiling, and it carries the risk of settling and insufficient structural integrity [113].

The method of biological fabrication is the only technology for which the sterilization step is strictly mandatory (“Yes”). Although low thermal conductivity can be achieved when producing panels with mycelium (0.04 W/mK), this method is the most time-consuming, as it requires extensive mushroom cultivation [114–116]. Compression molding and hot pressing are adaptive processes, as these methods have three main stages (washing, cutting, and drying) with a “No/Yes” status. Depending on the raw materials delivered to the factory, these stages can be included or skipped. However, they do not require sterilization (“No”) [45,104,117].

The literature data analysis shows variability in technological parameters depending on fabrication method and raw material type (Table S1 [Supplementary Materials]). Table S1 summarizes the main manufacturing methods, such as hot pressing, compression molding, wet process, air-laid process, needle-punching, hot drying, freeze-drying, and bio-fabrication, including the type of raw material, processing conditions, density

range and thermal conductivity range, advantages, limitations, scalability potential, and main challenges.

The comparison analysis in Table S1 shows that the most promising methods in terms of thermal insulation are biological fabrication (mycelium-based) and needle-punching. Mycelium grown on thin white ash chips yields an exceptionally low thermal conductivity range of 0.0313–0.0379 W/m K [118], outperforming traditional loose vegetable fibers. Similarly, needle-punched pure sheep wool mats achieve a competitive thermal conductivity of 0.031–0.034 W/mK [119,120].

For the structural integrity and load-bearing application, hot pressing is the most reliable method. Within high pressure applied during the process of 2.0–15.0 MPa and temperatures above 100 °C, resin curing (e.g., urea-formaldehyde or pMDI (polymeric diphenylmethane diisocyanate)), yielding high internal bond (IB) strength [117]. The mechanical properties of mycelium composites remain unsuitable for load-bearing building structures (for example, the flexural strength is only 0.063 MPa) [121].

Air-laid and hot-pressing technologies demonstrate the highest commercial scalability. Air-laid technology was originally developed for high-speed, continuous roll-to-roll texturing lines in modern nonwoven textile mills, easily handling highly porous matrices of up to 90% [69]. Hot pressing is also scalable, as it directly simulates the automated, high-throughput production lines already standard in global commercial particleboard and MDF plants [32,95]. In contrast, batch-based protocols such as lyophilization or long mycelial incubation times (7–42 days) face significant scalability challenges [116,122,123].

Room-temperature drying molding methods (using rapidly curing binders such as liquid sodium silicate left to vaporize at room temperature) avoid the energy costs associated with industrial ovens [102]. This contrasts with the high thermal inputs of freeze-drying (operating down to −83 °C) or hot pressing (up to 220 °C) [89,104,124].

The most energy-intensive and technically demanding process is hot pressing, where average temperatures reach approximately 140–190 °C, with pressures ranging from 2 to 16 MPa [41]. Wood-based by-products often require longer pressing cycles (up to 20 min or more), while agricultural by-products can be processed faster (6–12 min) [89], though sometimes requiring higher temperatures (up to 220 °C) to activate binders.

Compression molding shows polar extremes, ranging from ambient temperature (23 °C) to 200 °C [125]; however, the pressure often remains minimal or near zero, suggesting a focus on shaping rather than high-density compaction.

To identify a clear industry leader among these fabrication methods, the specific application of the final product must first be defined, as performance criteria vary significantly across different insulation types (boards, mats, or loose-fill) used in wood frames or sandwich panels [113,120]. For instance, mechanical stability is critical for rigid structural panels but irrelevant for loose-fill insulation, where low density and ease of application are prioritized. While application dictates physical needs, critical parameters such as moisture absorption, fire resistance, production cost, microbiological stability, and product life cycles remain universally essential across all methods. However, conducting a comparative evaluation for the current dataset is currently impossible due to severe data gaps in the existing literature. Most studies either exclude measures or conduct them strictly within a limited, non-standardized testing way.

Furthermore, laboratory testing conditions, including sample thickness and shape, are frequently dictated by specific testing standards rather than real-world optimization [125,126], even though material thickness directly determines the final R-value properties [127]. Real-world performance is best evaluated at the system level through climate chambers or building simulations, which reveal complex hygrothermal behaviors. For example, system-level testing shows that, while U-values can remain identical

across different materials (e.g., $0.15 \text{ W/m}^2 \text{ K}$), biomaterials like hemp-lime and wood fibers show better heat storing and releasing capabilities under cyclic boundary conditions compared to mineral wool [128]. A detailed thermal performance analysis shows that differences in insulation properties are much stronger when materials are tested individually rather than when integrated into composite systems, such as External Thermal Insulation Composite Systems (ETICS) or sandwich panels [129,130].

Due to their natural ability to absorb and release moisture continuously, bio-based materials buffer indoor humidity, which helps mitigate intense shifts in room temperature during weather cycles. The long-term durability and practical success of these natural materials depend far more on external weather dynamics than on the specific type of core insulation or its standalone thermal conductivity [130,131].

Humidity is a critical parameter in mold formation. This risk is particularly serious for interior insulation, which is the most vulnerable type of insulation in terms of condensation and moisture accumulation [132]. Effective protection of biomaterials without toxic chemicals requires strict humidity control and careful management of the hygrothermal properties of walls to prevent condensation [22,132]. At a relative humidity of 90–95% and a temperature of 22°C , mold can colonize wood within 7–14 days [133], and when the moisture content of wood reaches 25–30%, the risk of façade and roof decay becomes critical [134,135].

Traditional preservatives, such as boric acid and boron compounds, are commonly used to protect biomaterials from mold growth. However, at high humidity (>90–95% relative humidity), these water-soluble preservatives are easily washed out, leaving the material vulnerable to decay [136]. Natural, eco-friendly alternatives, such as chitosan, propolis extract, and essential oils (tea tree, thyme, clove, lemon, peppermint), show promising results but have limitations related to volatility, durability, and cost [96]. The integration of oak chips into MDF production represents an effective, natural method for increasing the strength and decay resistance of boards, demonstrating a mass loss of less than 25%, allowing them to be classified as “durable” or “very durable” [137].

3.4.1. Influence on Thermal Properties

The molding method and process parameters determine the ability of biomaterials to impede heat transfer by regulating the material’s density and internal porosity. For bio-based insulation (hemp, wood fiber, straw, cellulose), thermal conductivity (λ) has a U-shaped or parabolic relationship with density [36]. In porous bio-insulation, total thermal conductivity λ_{total} is the sum of solid conduction, gas conduction, and radiation. In high-density boards (hot pressing), heat is transferred through the solid skeleton of the material (conduction), while in porous mats (air-laid, freeze-drying), heat transfer is reduced by immobilizing air in micropores and limiting convection. Lowering density increases porosity, but it also creates large, open air gaps that allow thermal radiation and free air convection to transfer heat. Conductivity remains high in this ultra-low-density range. At the critical point, solid matter is minimized, air pockets are small enough to prevent convection, and natural fibers optimally obstruct thermal radiation. At this stage, the thermal conductivity will be determined by the raw material [36]. The density range across the production methods is shown in Figure 11.

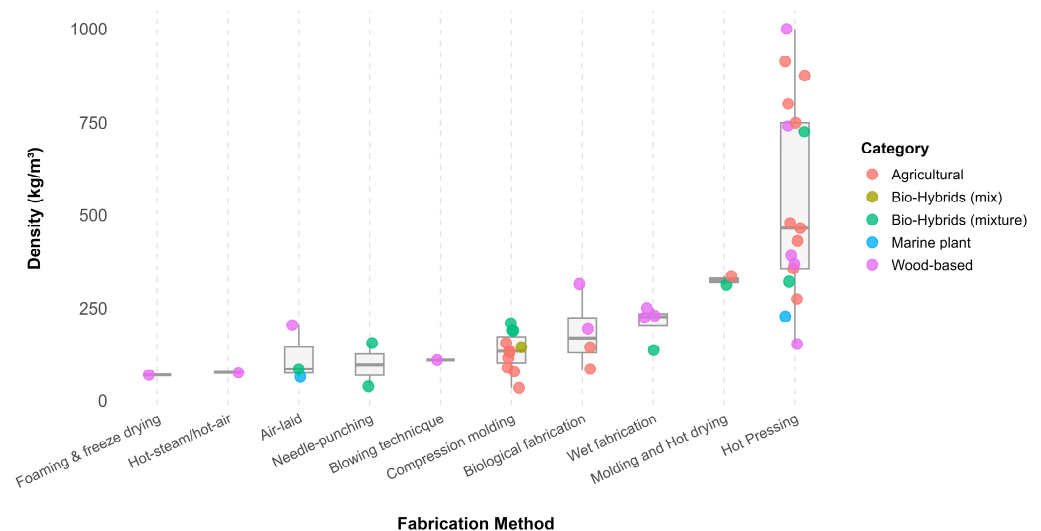


Figure 11. The distribution of density values for different manufacturing methods.

Methods that exclude mechanical pressing, such as foaming and freeze-drying, hot-steam/hot-air, and air-laid, produce stable, low-density structures (below 200 kg/m^3). At the same time, the hot-pressing method shows an extremely wide range of density distribution (from 150 to 1000 kg/m^3). This is due to the fact that the largest amount of data is available for this method. Also, varying the process pressure (2 – 16 MPa) and temperature directly regulates the volume of residual porosity of the material [75]. Biological fabrication (mycelium) and wet fabrication methods allow for the production of lightweight boards due to natural volume filling (mycelium growth or moisture removal through a mesh) without rigid mechanical compaction of the structure [108,109].

Figure 12 shows that foaming with freeze-drying and needle-punching methods exhibit the lowest and most consistent thermal conductivity values (around 0.04 W/mK) due to highly porous structures. Mycelial (bio-fabrication) materials show a wide range of values, indicating the difficulty of controlling the growth process and the heterogeneity of the resulting structure. Hot pressing contains the most data points, as it is one of the most widely used methods. This fabrication minimizes porosity and compacts the material (density up to 800 kg/m^3) due to high mechanical pressure, which leads to an increase in thermal conductivity up to 0.10 – 0.14 W/mK [103].

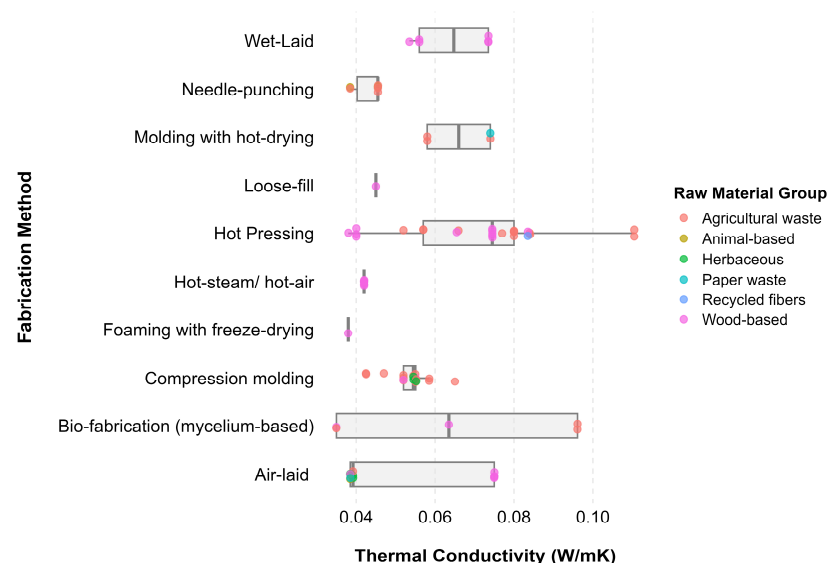


Figure 12. The distribution of thermal conductivity values for different manufacturing methods.

In hot-pressing methods, varying the time (from 4 to 25 min) and temperature (130–200 °C) allows for the structure to be adjusted: for example, whole olive leaf slabs panels have a thermal conductivity of 0.065–0.085 W/mK [45], while coconut coir or rice husk panels show a thermal conductivity of around 0.05–0.073 W/mK [112,138]. Biofabrication allows the production of ultra-light structures (20–36 kg/m³) with competitive thermal conductivities in the range of 0.031–0.053 W/mK; however, these materials show a high dispersion of values due to the difficulty of controlling mycelial growth and structural heterogeneity [86,118].

3.4.2. Influence on Mechanical Properties

Key mechanical properties of bio-based thermal insulation presented in the literature are compressive strength, flexural strength or Modulus of Rapture (MOR), and Modulus of Elasticity (MOE).

The compressive strength of bio-insulation is determined by several key factors such as density, binder type and ratio, raw material characteristics, porosity, pretreatment, and moisture content. Higher-density materials generally show greater strength [139]. During the production process, such as pressing or wet-laid, the mat is compressed, eliminating large voids and increasing the density of the material. Pressing time and temperature affected the density of panels made from whole olive leaves with a thickness of around 6 mm [45]. However, improved mechanical properties occurred for panels made from crushed material and not for the whole leaves.

Figure 13 shows the positive correlation between compression strength and density of bio-based insulation materials across different fabrication methods and raw material categories.

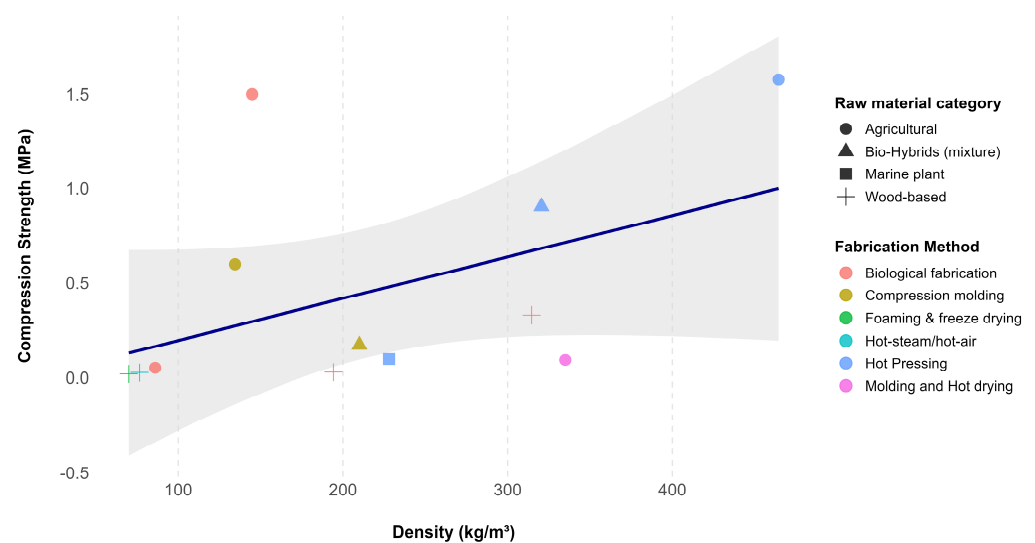


Figure 13. Correlation between compression strength and density of bio-based insulation materials across different fabrication methods and raw material categories. The blue line represents the linear regression trend, and the grey shaded area indicates the 95% confidence interval.

The hot-pressed materials showed a wide range of values due to both their density and the addition of binders, which strengthens the material. Compressive strength values for panels made from a paper pulp and rice husk composite are 20.19–21.23 MPa [140], which is explained by the creation of a dense, rigid matrix due to the adhesive component and the interweaving of the cellulose fibers of the paper during drying. Molding with hot drying allows for moderate strength (1.2 MPa) to be achieved for wheat straw boards due to the addition of a metakaolin binder and a foaming agent [141], which form a stable porous structure. Without the introduction of such rigid matrices (e.g., for a mixture of

bran and banana peel), the material behaves as a plastic damper under load, showing only 20–170 kPa at 10% deformation [142].

Panels made of sphagnum moss and straw molding with liquid glass under pressure have a slightly lower compressive strength in the range of 0.20–0.21 MPa [102] due to the lack of thermal polymerization of the binder and the elastic “rebound” of the plant fibers after the press is removed.

Bio-fabrication (mycelium-based) shows low and insufficient strength for load-bearing applications (0.013 MPa) on a substrate made of beet pulp and husks [121] because fungal hyphae create a light, spongy, airy foam that easily collapses under compression, as well as in the loss of mass from the substrate itself, which the fungus consumes during growth.

Changing heat treatment conditions directly controls the balance between density, internal bonding (IB), and flexural strength (MOR). Traditional hot pressing creates a thermal gradient, causing binder polymerization to occur unevenly across the board thickness. The use of high-frequency currents [117] solves the core heating problem, increasing IB from 0.0096 to 0.0132 MPa, but reduces MOR by 37% (from 0.89 to 0.56 MPa). A conventional press heats the board from the outside in, causing the outer layers of the material to become more compact (creating a so-called vertical density profile). The high-frequency method heats the board uniformly across its entire thickness, resulting in a lower density at the surface. Since the outermost layers bear the stress of the tension and compression during bending (MOR test), the less dense surface of the boards is lower than that of a conventional press [117]. Increasing the exposure time during classical hot pressing [138] optimizes the plasticization of the lignocellulosic matrix (change in flexural properties by 7%) but limits economic feasibility, since it unreasonably increases the cost of production [126].

Needle-punched mats and air-laid materials have tensile strengths in the range of 2.5–130 kPa, which depends on the degree of fiber interweaving and the addition of thermoplastic fibers (e.g., PLA, PE, PP) [69,143].

3.4.3. Influence on Hydrothermal Properties

Since bio-based insulation materials are of an organic nature, their physical properties are characterized by high hygroscopicity and water absorption capacity (WA), which strongly depends on the presence of hydrophobic agents and the porosity specified by the production method. Moisture absorption decreases the insulation value of bio-based materials through two main mechanisms: by replacing trapped air with water (which conducts heat much faster) and by physically altering the material's structure over time [144].

During humidity conditioning, biomaterials mitigate temperature peaks through water sorption/desorption processes [128]. Natural materials generally exhibit a sigmoidal (S-shaped) Type II isotherm. The overall process creates a loop due to a phenomenon called sorption hysteresis. These curves are the basis of hygrothermal modeling, which predicts whether condensation will form inside walls. Materials like cork, hemp, and wood fiber rely on their ability to safely adsorb and release ambient moisture [65].

The production method reduces capillary volume (large pores) but has little effect on cell wall sorption at the micro level. When bio-based materials are immersed directly into water, porous structures without water repellents show extreme water absorption. For example, for wet-laid bark boards, water absorption ranges from 55% to 380%, and thickness swelling reaches 23% [93]. Hemp-on-lime composites, made by molding with the drying method, absorb five times more water than hemp–lime composites [145].

Manipulating thermopressing parameters (increasing temperature and time) helps reduce thickness swelling of coconut coir boards due to restructuring of the carbohydrate complex [126]. Using a combination of hot air (up to 120 °C) and hot steam for 30 s to activate the LMS and pMDI enzymatic system reduces water absorption to 0.52 kg/m² [146]. Using the air lay-up method with heat-setting of PLA fibers (at 160 °C) ensures water absorption of mats in the range of 0.5–8.5 kg/m² and a water vapor diffusion resistance coefficient (Sd) of 2.53–2.66 [143].

Water has a thermal conductivity of ~0.6 W/mK (which is 15 times higher than air). It should be emphasized that methods that leave the material unprotected from moisture (for example, molding without water repellents) lead to a sharp drop in thermal resistance under real-world operating conditions.

3.4.4. Environmental Aspect

The ecological footprint and operational durability of bio-insulation are determined by the balance between the energy intensity of the technological process, the origin of the binders, and the resistance of the organic raw materials to biodegradation.

On the one hand, the use of agricultural and industrial waste (rice husks, hemp husks, sawdust, straw, bark) in almost all methods increases the environmental attractiveness of the materials through the utilization of by-products (agricultural waste) [112,141]. On the other hand, methods such as hot pressing at high temperatures (140–190 °C, up to 220 °C) and long cycles (up to 20 min), as well as freeze-drying processes, are characterized by colossal energy consumption during the production stage [77,89].

Biofabrication (mycelial cultivation) is promoted as carbon-negative. However, the CO₂ released by fungi during metabolism creates a carbon footprint of 0.3668 kg CO₂ per kg of material, even at the laboratory stage [147]. Furthermore, during growth, fungi consume the substrate itself, causing mass loss [122,123].

A significant problem with biomaterials is their vulnerability to microbial growth during use. Studies of mold resistance show that, for the differently manufactured boards, the lowest mass loss due to decay was recorded for dry-pressed boards, which was slightly higher for wet-laid materials, and the most vulnerable were flexible porous mats [148]. Mycelial composites are even more susceptible to mold attack than pure hemp or cork [65].

Environmental friendliness depends not only on the pressing energy but also on the chemistry. The toxicity of synthetic resins (e.g., phenol formaldehyde PF or pMDI) [149] complicates subsequent recycling/composting of the material, as opposed to completely “green” methods (LMS enzymes, mycelium, or chitosan).

Environmental properties in construction include fire safety. Since bio-based feedstocks are flammable, methods requiring the addition of large amounts of borates/flame retardants (such as the addition of borax in the wet method [140]) must be assessed in terms of the environmental friendliness of their emissions.

The reviewed literature provides very limited data on the thermal stability of bio-materials (4 out of 11 manufacturing methods). A panel produced by hot pressing has the best thermal stability (stable up to above 306 °C) [43], with density 660–790 kg/m³. Higher-density bio-composites have greater thermal inertia. When exposed to extreme temperatures or fire, a denser material sustains thermal degradation longer because of larger physical mass per unit volume, capable of absorbing and dispersing heat [150].

4. Conclusions

This review provides a comprehensive technical analysis of how manufacturing conditions and processes determine the multifunctional performance of lignocellulose-based thermal insulation. Unlike previous reviews, which have primarily focused on the properties of individual raw materials or life cycle assessments, this study established a cause-and-effect relationship between pretreatment methods, binders, and structural molding parameters and the final thermal, mechanical, and hygrothermal performance of bio-based insulation.

The comparative analysis demonstrates that there is no single “ideal” manufacturing method. The choice of manufacturing method should be adapted to the intended structural application.

- **Thermal optimization.** The lowest thermal conductivity (0.031–0.040 W/mK) is achieved using methods that avoid strong mechanical pressing, such as needle-punching of pure animal/plant fibers, foaming via freeze-drying, and biological (mycelium-based) manufacturing. These methods preserve maximum microporosity and immobilize air pockets, preventing convective heat transfer.
- **Mechanical integrity.** For rigid semi-structural insulation boards where structural integrity is critical, hot pressing and compression molding remain the most reliable methods. Pressing at pressures of 2.0–15.0 MPa and temperatures above 100 °C ensures maximum internal bond strength (up to 1.2 MPa) and ultimate flexural strength (MOR) due to matrix compaction and uniform binder curing.
- **Environmental impact.** Room-temperature molding with cold drying or loose-fill blow molding demonstrates the lowest energy consumption, avoiding the intense heat treatment (up to 220 °C) required for industrial pressing or energy-intensive vacuum freezing cycles during lyophilization.

The main technical limitations of bio-insulation materials include the hydrophilic nature of raw biomass, which leads to extremely high water absorption (55–380%), which replaces entrapped air with water and reduces thermal insulation properties. High moisture accumulation and the use of organic bio-binders (starch, casein) also lead to rapid colonization by mold or decay fungi. Furthermore, replacing formaldehyde-based synthetic resins with environmentally friendly binders significantly degrades mechanical properties and mold resistance, requiring expensive or volatile natural additives. Barriers to scalability are related to the availability of production lines. Unlike pneumatic molding and pressing lines, which correspond to standard MDF/chipboard infrastructure, biological production is limited by long incubation times (7–42 days) and mandatory substrate sterilization.

To bridge the gap between the laboratory development stage of bio-insulation and industrial application, future studies must prioritize critical areas. Future research should focus on developing moisture-resistant bio-binders derived from starch, tannin, or lignin that prevent mold growth without relying on toxic synthetic chemicals. Testing must shift from controlled laboratory environments to real-world, system-level wall assemblies to evaluate how seasonal hygrothermal behavior impacts long-term thermal conductivity. Biological fabrication methods require optimization to shorten the lengthy 7–42-day mycelium cultivation cycle and minimize the high energy consumption of substrate sterilization. Comprehensive techno-economic analyses are needed to adapt existing industrial MDF and particleboard pressing lines for the scalable production of low-density, high-porosity bio-insulation panels without sacrificing their structural integrity.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app16125866/s1>.

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Abbreviations

The following abbreviations are used in this manuscript:

CNB	Carbon-Neutral Buildings
Cp	Specific Heat Capacity
EPS	Expanded Polystyrene
EU	European Union
FTIR	Fourier Transform Infrared Spectroscopy
GHG	Greenhouse Gases
IB	Internal Bonding
IEA	International Energy Agency
LCA	Life Cycle Assessment
LMS	Laccase-Mediator System
MBV	Moisture Buffer Values
MDI	Methylene Diphenyl Diisocyanate
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
MPa	Megapascal
MUF	Melamine Urea Formaldehyde
NaOH	Sodium Hydroxide
NRC	Noise-Reduction Coefficient
NZEB	Net Zero Energy Building
OSB	Oriented Strand Board
PVA	Polyvinyl Acetate
PE	Polyethylene Terephthalate
PET/rPET	Polyethylene/Recycled Polyethylene Terephthalate
PF	Phenol Formaldehyde
PLA	Polylactic Acid
PU	Polyurethane
pMDI	Polymeric Diphenylmethane Diisocyanate
PP	Polypropylene
RH	Relative Humidity
R-/λ-value	Thermal Resistance/Thermal Conductivity Coefficient
rpm	Revolutions Per Minute
Sd	Water Vapor Diffusion Equivalent Air Layer Thickness
SEM	Scanning Electron Microscope
SIPs	Structural Insulated Panels
TGA	Thermogravimetric Analysis
TMP	Thermomechanical Pulping

TS	Thickness Swelling
UF	Urea-Formaldehyde
UV	Ultraviolet
U-value	Thermal Transmittance
WA	Water Absorption
w/w	Weight by Weight (e.g., 8% w/w)

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