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Review

Mycelium-Based Thermal Insulation for Domestic Cooling Footprint Reduction: A Review

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Abstract: Domestic cooling demands in arid and hot climate regions, including Qatar, induce a significant challenge to reduce the area's cooling energy consumption and carbon footprint, primarily due to the heavy reliance on electricity-intensive air conditioning systems. The inadequacy and inefficiency of conventional construction and insulation materials and their improper implementation further exacerbate this issue. Considering such challenges, this research comprehensively evaluates an unconventional and innovative solution recently proposed for this purpose: mycelium-based thermal insulation. Mycelium is the vegetative, thread-like structure of fungi, consisting of a network of branching hyphae that facilitate nutrient absorption and environmental interactions. This review paper analyses mycelium-based composites, focusing on their mechanical, physical, and chemical characterization. It also explores the potential of mycelium as a sustainable solution for indoor temperature regulation, particulate matter absorption, and bioremediation. Moreover, this review examines various available insulation materials and highlights the unique advantages offered by mycelium-based composites. As a result, the literature review indicates that mycelium exhibits exceptional thermal and acoustic insulation properties owing to its low thermal conductivity, favorable water absorption coefficient, porous structure, and considerable mechanical strength. This porous architecture facilitates efficient air purification, improving indoor air quality. Additionally, mycelium shows promise in actively degrading pollutants such as hydrocarbons, heavy metals, and pesticides in soil and water.

Keywords: mycelium; thermal insulation; indoor temperature regulation; particulate matter absorption; bioremediation; carbon footprint

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1. Introduction

Ever-increasing energy consumption, the consequent rising carbon emissions, and reliance on century-old non-renewable energy resources entail considerable risks to health, the environment, and the economy [1]. Buildings are substantial in global energy consumption and contribute significantly to energy-related carbon dioxide (CO_2) emissions. In 2020, buildings were responsible for 36% of worldwide energy consumption and contributed to 37% of energy-related CO_2 emissions. The operational emissions associated with the global buildings sector, including direct and indirect emissions from heating, cooling, lighting, and more, reached 8.7 gigatons. Specifically, direct energy-related emissions from building operations amounted to less than three gigatons of CO_2, while indirect emissions from electricity use totaled up to 5.8 gigatons of CO_2 [2]. The process of heat transfer through walls and roofs by conduction is a significant and influential factor in the overall heating/cooling load of a building. Hence, the effective use of insulation significantly reduces the heating/cooling load, consequently minimizing the total energy requirement for those purposes. Efficient insulation materials can reduce heat transfer by conduction and minimize the load on cooling systems and the energy demand. Therefore, this reduction in heating/cooling load contributes significantly to lower energy consumption and increases the overall efficiency of energy usage in buildings [3]. Additionally, it improves the comfort experienced by the occupants.

2. Methodology

We conducted a comprehensive literature review using search engines like Google, Google Scholar, Scopus, and ScienceDirect databases. Our search strategy involved employing a set of keywords including "mycelium", "fungal insulation", "mycelium insulation", "mycelium thermal insulation", "mycelium acoustic insulation", "particulate matter", "indoor temperature regulation", "bioremediation", "thermal conductivity", "cooling", "heating", "carbon footprint", and "embodied energy". The inclusion criteria for our search encompassed papers published between 2017 and 2023, primarily focusing on the utilization of mycelium as a foundational material for thermal insulation in residential buildings. This involved exploring the multifaceted aspects of mycelium and its diverse applications. Additionally, we aimed to examine fungal adaptations and ecological roles, particularly concerning nutrient exchange, decomposition, and bioremediation. Our scope extended to investigating mycelium-based composites' mechanical, physical, and chemical attributes while evaluating conventional organic and inorganic insulation materials. The ultimate objective was to uncover the promising potential of mycelium as an eco-friendly solution for indoor temperature regulation, particulate matter absorption, biodegradability, and environmental impact. In the initial screening phase, we reviewed titles, abstracts, and various types of research content, including research articles, review articles, books, book chapters, theses, and reports. Exclusion criteria were applied to papers not written in English and those that did not pertain to the examination of mycelium for thermal insulation purposes or other environmental purposes, as indicated earlier. A total of 200 relevant sources were identified through our search engines, and the study selection process of our review is depicted in Figure 1. References that did not directly align with the scope of our review, focusing mainly on mycelium as a construction material rather than investigating its performance as a sustainable thermal insulation material, were also excluded from our analysis.

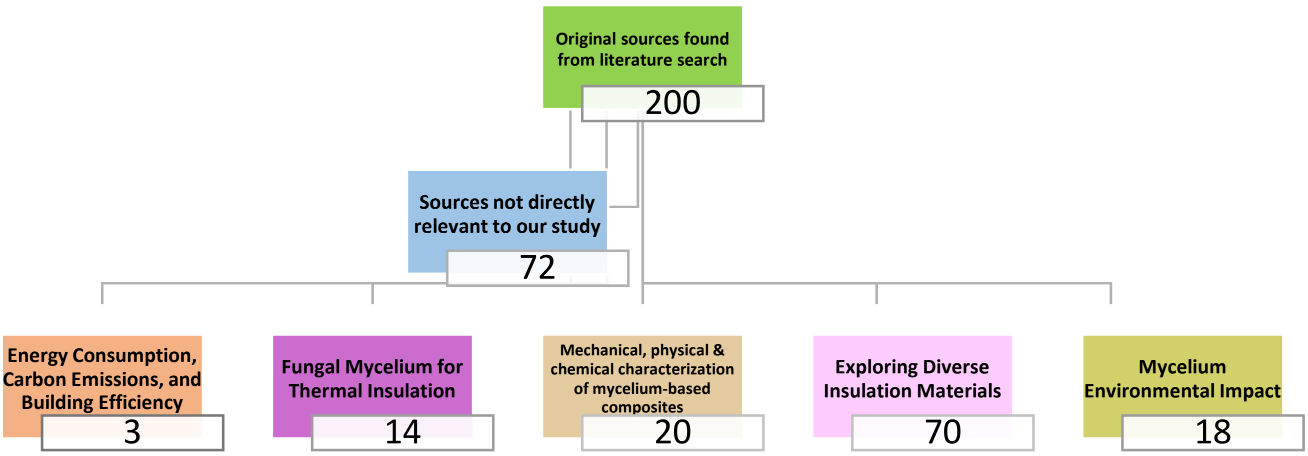

Figure 1. Study selection flow chart.

3. Mycelium as a Base for Thermal Insulation

3.1. Exploring the Hidden Dimension of Fungi

Mycelium has recently garnered increasing attention from academic and industrial sectors due to its minimal energy requirements during growth, absence of by-product generation, and extensive potential applications [4]. Mycology, a subdivision of microbiology, delves into the domain of fungi—a multifaceted and expansive kingdom that incorporates molds, yeasts, and various types of mushrooms [5]. While mushrooms are the visible reproductive structures of fungi, most of their bodies grow below ground as a woven-like network called mycelium. Mycelium is the root-like formation of a fungus, made up of a network of thin, white threads that range from 1 to 30 micrometers in width (Figure 2) [6]. Bio-derived materials present a remarkable opportunity for exploring architectural and product design innovations. Among these, mycelium-based materials stand out as particularly promising, offering a significant pathway for creating environmentally conscious materials that leave minimal impact throughout their entire lifecycle. Mycelium filaments have multiple layers that exhibit varying chemical compositions, comprising proteins, glucans, and chitin [7]. Mycelium has been recognized as the most expansive living organism on Earth. The substrate functions as a nutritive reservoir of organic matter that sustains the expansion of the mycelial infrastructure. In natural ecosystems, these organic substances commonly originate from the residues of organisms, including plants and animals, and their by-products found within the surroundings [8]. A single cubic inch of soil has the potential to harbor up to 8 miles of mycelial cell networks [9]. The life cycle of fungi typically remains inconspicuous until the development of reproductive structures known as fruits. Given that fungi propagate via spores, the efficacy of their life cycle hinges upon the successful formation of these spore-producing organs, commonly referred to as mushrooms [10]. Fungi exhibit a widespread presence across diverse ecosystems worldwide, showcasing remarkable resilience under extreme conditions such as deserts, polar regions, aquatic depths, and high salinity zones. Some fungal species demonstrate notable adaptability when temperatures surge during the warmer summer. Among the fungi varieties well-suited for elevated temperatures, those suitable for indoor cultivation encompass the Pink Oyster (21–29 °C), Reishi (21–27 °C), Antler Reishi (15.6–26.7 °C), Shiitake (10–26.7 °C), and King Stropharia (15.6–26.7 °C). For outdoor mushroom patches and plug spawn, favorable choices include the Phoenix Oyster (18–24 °C), Reishi (21–27 °C), Shiitake (10–26.7 °C), and Garden Giant (4.4–32.2 °C) [11].

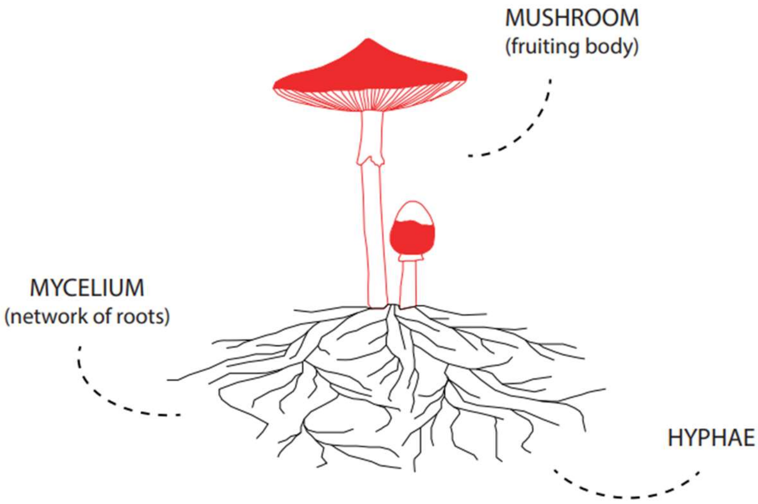

Figure 2. Schematic representation of mycelium structure [10].

Materials derived from mycelium can enhance the air quality within indoor environments. Fungal mycelium has been shown to possess natural air-purifying capabilities, particularly in terms of particulate matter (PM) filtration. The porous structure of mycelium enables it to trap and filter airborne particles, including $PM_{2.5}$ and PM_{10}, thereby enhancing indoor air quality [12]. Additionally, mycelium has the potential to regulate indoor humidity. The hygroscopic nature of the mycelium allows it to absorb and release moisture, helping to maintain optimal moisture levels. This natural humidity regulation contributes to a comfortable indoor climate [13]. Furthermore, mycelium can sequester over 16 metric tons of carbon from the atmosphere within a month [14].

3.2. Mycelium Growth Process

The fundamental process of cultivating mycelium composites is comparable to the conventional approach employed in mushroom cultivation. The procedure begins with introducing mushroom spores, essential nutrients, and water into a culture dish, followed by an incubation period lasting 7 to 14 days until it completely covers the dish. Subsequently, a sterilized growth substrate is formulated, comprising organic components such as brown rice, roasted buckwheat, wheat, and straw. A small segment of mycelium is transplanted into this substrate to facilitate further incubation. In this phase, optimal humidity levels of around 98% and a controlled ambient temperature of 24–25 °C are pivotal factors governing mycelium expansion. The provision of fresh air further contributes to a favorable growth environment. Upon complete colonization of the substrate by the mycelium, a drying process is initiated at elevated temperatures for several hours. This heat treatment deactivates the hyphae and arrests the growth progression, ultimately yielding a mycelium composite material (Figure 3) [15].

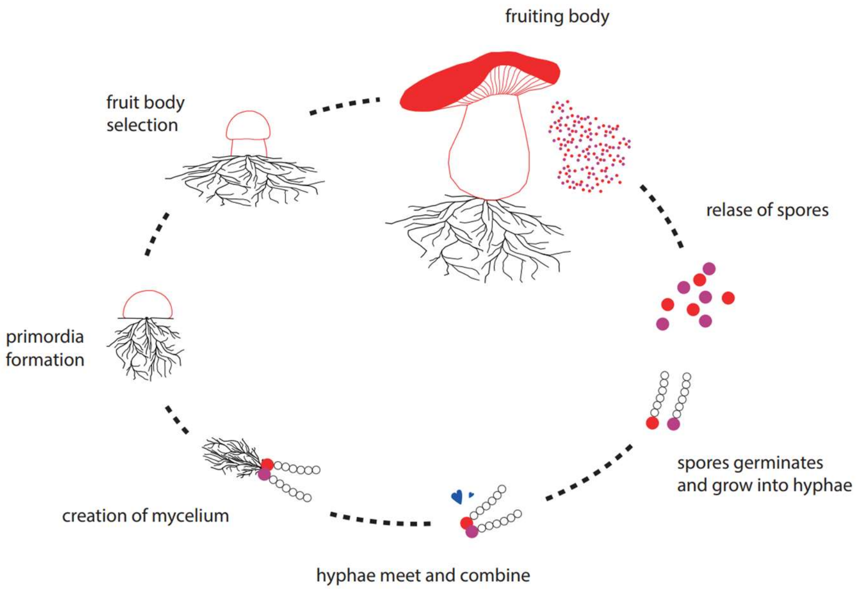

Figure 3. Schematic representation of fungal life cycle [10].

3.3. Mycelium: Insights into its Applications

Mycelium-based materials are versatile biomaterials that have numerous applications across various industries. In medicine, these materials possess exceptional potential for wound healing, tissue engineering, and biosensors due to their remarkable biocompatibility, biodegradability, antimicrobial activity, antioxidant activity, and tunable mechanical properties. Within the cosmetics industry, mycelium-based materials offer an array of applications, including skin whitening, anti-aging, moisturizing, and sunscreen products, due to their unique properties, such as tyrosinase inhibition, collagen synthesis stimulation, water retention, and UV protection. Mycelium-based materials can be used for food packaging, cushioning, and insulation products due to their lightweight, porous, thermally insulating, fire-retardant, and water-repellent characteristics. Additionally, mycelium-based materials can be used in construction for building blocks, panels, tiles, bricks, and furniture products due to their acoustic absorption, thermal insulation, fire resistance, and aesthetic appeal properties [16].

3.4. Fungal Adaptations and Ecological Roles: Insights into Nutrient Exchange, Decomposition, and Bioremediation

Fungi, like many microorganisms, are heterotrophic organisms. Therefore, they cannot manufacture their own food and must obtain organic nutrients from the external environment, absorbing them through their walls. Most mushrooms that thrive in forest environments are intricately connected to trees through a symbiotic relationship. This interaction, referred to as mycorrhiza, establishes a connection between the root extremities of trees and the vegetative structure of fungi (Figure 4).

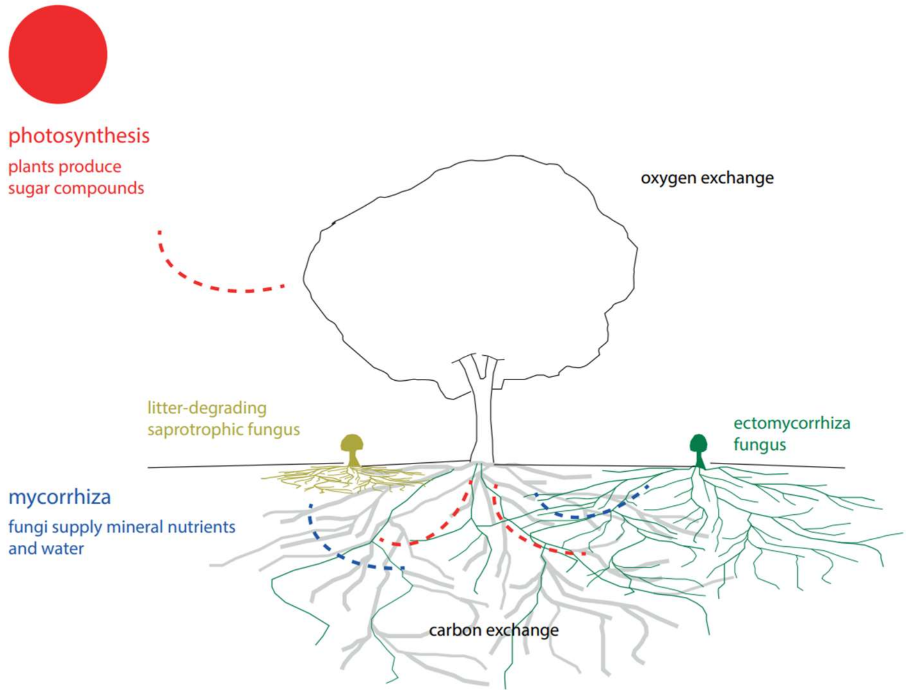

Figure 4. Schematic representation of mycorrhiza: Mutualistic association between tree roots and fungal mycelium [10].

The mycorrhizal association is mutually advantageous, involving a reciprocal exchange of nutrients. One organism offers substances the other cannot produce or obtain directly from the soil. Broadly, mushrooms assist plants in acquiring minerals and water from the soil, while in return, plants provide the fungus with sugar compounds. Saprophytism constitutes another significant ecological strategy among fungi, mainly observed in species thriving on grassy terrains, decaying wood, or organic waste. In this context, the fungal function primarily involves decomposition, as it metabolizes organic materials, concurrently replenishing nutrients in the soil. Finally, certain fungi adopt a parasitic lifestyle. Various forms of parasitic relationships can be observed, from species that target and inhabit viable hosts such as trees, plants, or insects without causing their demise to those that assail weakened hosts, consequently expediting their end. Typically, these parasitic fungi are microscopic mushrooms. Most gourmet mushrooms are saprophytic, wood-decomposing fungi, and they are the premier recyclers on the planet. The mycelial network is designed to weave between and through the cell walls of plants. Fungi are fascinating and mysterious organisms that mycologists study to discover their secrets. Fungi can act as filters or depurators for polluted soils. In industrialized areas, soils are contaminated by various pollutants (petroleum-based compounds, heavy metals, pesticides, etc.) and even radioactive wastes. Mushrooms can absorb toxins into their tissue, including heavy metals, but they become inedible. Some species can be used to clean up contaminated environments through bioremediation. Different techniques have been patented in the last 15 years, and different bioremediation companies have been established to deal with toxic waste [17].

The contemporary world is grappling with a substantial challenge in curtailing its energy consumption attributed to cooling, a critical constituent of the residential carbon footprint. Conventional cooling strategies, primarily reliant on air conditioning paradigms, engender elevated energy usage, thus yielding consequential environmental and socioeconomic ramifications. Furthermore, the prevalent utilization of conventional insulation materials often manifests as ill-suited for the exigencies of prevailing climatic extremities, thereby amplifying inherent operational inefficiencies. This review paper aims to thoroughly examine the utilization of mycelium-based thermal insulation to significantly reduce the environmental impact associated with domestic cooling. The paper embarks on a comprehensive journey by investigating the multifaceted dimensions of mycelium, encompassing its concealed attributes within the realm of fungi, its intricate growth process, diverse applications across various fields, and its ecological significance in nutrient exchange, decomposition, and bioremediation. Mycelium-based composites' mechanical, physical, and chemical characteristics are systematically scrutinized, contributing to a comprehensive understanding of these materials' structural and functional properties. In tandem, an inclusive overview of conventional insulation materials is presented, facilitating a holistic evaluation of mycelium-based solutions within the larger context of insulation technology. The paper particularly emphasizes the potential of mycelium to offer sustainable and innovative avenues for indoor temperature regulation, efficient particulate matter absorption, and inherent biodegradability.

4. Mechanical, Physical, and Chemical Characterization of Mycelium-Based Composites

Recent advancements in developing mycelium-derived bio-composite materials have generated significant interest in design and architecture due to their potential as sustainable and biodegradable alternatives to conventional insulation materials. Mycelium-based insulation has emerged as a promising solution that offers unique mechanical, physical, and chemical characterization (Table 1).

Table 1. Properties of mycelium-derived composites.

Strain	Substrate	Density kg m^{-3}	Thermal Conductivity w $m^{-1}K^{-1}$	Young's Modulus MPa	Compressive Strength MPa	Water Absorption Rate (%)	Ref.
Trametes versicolor	Hemp, flax, flax waste, pine softwood, wheat straw	94, 99, 135	0.0404, 0.0419, 0.0578	1.19, 1.32, 1.14	0.35–0.45	24.45–30.28	[18]
Oxyporus latermarginatu, *Megasporoporia minor*, *Ganoderma resinaceum*	Wheat straw	51.098, 61.967, 57.452	0.078, 0.079, 0.081	N/A	N/A	N/A	[19]
Pleurotus ostreatus	Rye berries	599	0.069, 0.070	N/A	N/A	N/A	[20]
Ganoderma lucidum, *Trametes versicolor*	Beech sawdust, beech SD supplemented with further nutrients, spent mushroom substrate, and SMS supplemented with further nutrients	190–226	0.045–0.077	N/A	0.0172–0.0421	N/A	[21]
Pleurotus ostreatus	Rice husks and sawdust	153–239	0.069–0.081	0.015–0.615	0.011–0.265	85.46–243.45	[22]
Trametes versicolor, *Trametes pubescens*	Beechwood sawdust	480, 515	0.057, 0.054	N/A	0.01–0.013	N/A	[23]
Pleurotus ostreatus	Saw dust-coir pith	183–225	0.069	0.133–0.411	0.0326–0.432	N/A	[24]
white-rot saprotrophic fungi	Wood pulp, millet grain, and wheat bran	160–265	0.05–0.07	N/A	0.35–0.570	N/A	[25]
Pleurotus florida	Rice straw	1420	0.029	N/A	8.7	17.2–37.6	[26]

Previous studies have focused on assessing these composites' strength, stiffness, toughness, and fatigue resistance through various testing methods, including tensile, compressive, flexural, and impact tests. These investigations have shed light on the composite's load-bearing capacity, deformation behavior, and resistance to mechanical stresses. Furthermore, the influence of various factors, such as mycelium species, growth conditions, and composite formulation, on mechanical performance has been explored to optimize the material design and enhance mechanical properties. Mycelium-based materials exhibit low density, sound insulation, and nonlinear behavior under tension and compression. The density of materials derived from mycelium falls within the range of 0.02 to 0.2 g/cm^3, comparable to or lower than that of EPS (0.01–0.2 g/cm^3). The properties of mycelium-derived materials are related to their porosity and microstructure, which affect their thermal conductivity and sound absorption coefficients. The thermal conductivity of mycelium-based materials varies from 0.03 to 0.07 W/m·K, which is similar to or lower than that of EPS (0.03–0.04 W/m·K). At the same time, the sound absorption coefficients of mycelium-derived materials fall within the range of 0.4 to 0.9 at frequencies between 500 and 2000 Hz, which are higher than those of EPS (0.2–0.4) [27]. A study investigated the mechanical properties of mycelium composites produced using *Trametes versicolor*, a white-rot fungus. Incorporating bacterial cellulose, a natural additive, further enhanced these composites. The inclusion of bacterial cellulose led to enhancements in both the internal bond strength and the mechanical adjustability of the mycelium composite materials. This review presents findings indicating that the dry density of the composite material varies within the range of 460.30 to 531.17 kg/m^3, with fluctuations corresponding to the bacterial cellulose content. Additionally, the findings demonstrate that the particle boards exhibit flexural strength and modulus values spanning from 1.46 to 2.94 MPa and 0.22 to 0.44 GPa, respectively [28].

A comprehensive study delves into utilizing mycelium-based bio-composite materials within the domains of design and architecture. The primary objective is to identify the optimal combination of fungal species and agricultural waste materials, yielding biodegradable, renewable, and innovative properties. The investigation encompasses four distinct fungi species—*Pleurotus pulmonarius*, *Pleurotus ostreatus*, *Pleurotus salmoneostramineus*, and *Aaegerita agrocibe*—alongside five types of plant waste—eucalyptus, oak, pine, apple, and vine woodchips. Multiple attributes are assessed, including pH, electrical conductivity, water content, carbon and nitrogen levels, mycelium growth rate, density, and quality assessment. The study's findings underscore that the most efficacious synergies emerged from *Pleurotus ostreatus* samples cultivated on apple or vine woodchips [29]. A recent investigation has explored the feasibility of employing mycelium bricks as a practical insulation solution for architectural structures. The study emphasized harnessing a specific type of basidiomycete fungi to cultivate mycelium bricks utilizing straw waste as the substrate. The researchers conducted an assessment to ascertain the thermal conductivity and specific heat capacity of these mycelium bricks. Subsequently, they compared these values with conventional insulation materials, such as EPS. The study revealed that mycelium bricks exhibit favorable thermal properties, offering a significant environmental benefit. The measured thermal conductivities of the tested samples ranged from 0.078 to 0.081 W/m·K, while the heat capacities ranged between 0.369 and 0.501 MJ/m^{3}K [19].

A group of researchers developed a green building material by preparing a lightweight mycelium brick. Mycelium was cultivated within the substrate and subsequently compressed within a mold to shape a brick structure. After being burnt, the resulting mycelium brick was tested for compressive strength and water absorption. The researchers found that this material could be used in constructing non-load-bearing walls, pending further research to achieve the required strength. The result obtained from the compression test is 0.347 N/mm^2, the water absorption test is 33.81%, density is 250 Kg/m^3 [30]. Another study investigated how increased proportions of high-silica waste influence the fire safety of mycelium composites. The authors thoroughly assessed their susceptibility to ignition compared to conventional synthetic construction materials like polystyrene and medium-density particleboard. The findings indicate that mycelium composites demonstrate superior fire performance characteristics such as reduced heat release rates, extended time to reach flashover, and reduced smoke and CO_2 emissions compared to synthetic materials. Additionally, including glass fines in the mycelium composites enhanced their fire safety properties by increasing their silica content and reducing their combustible material content [31].

Additional research explores the influence of various factors on the compressive strength of mycelium-based bio-composites. The study examines specimens cultivated using the Gray Oyster mushroom strain (*Pleurotus ostreatus*) on three distinct substrates: sawdust, straw, and a combination of sawdust and straw, both with and without supplementation. The research reveals that both the type of substrate and the presence of supplementation and their combined effects exert noteworthy impacts on compressive strength. Notably, the compressive strength values ranged from 0.02 MPa to 0.14 MPa, significantly lower than those of traditional materials. Additionally, the paper highlights that straw-based and mixed-substrate samples exhibited more significant strain at failure than sawdust-based samples, indicating a more elastic behavior [32].

Another research examines how the growth medium composition can impact the properties of fungal mycelium. The authors conducted experiments using *Ganoderma lucidum* mycelium, grown in various variants of potato dextrose broth (PDB). The results revealed that modifying PDB with d-glucose or lignin influenced the mycelium's morphology, hydrodynamics, and mechanical properties. Mycelium cultivated in PDB enriched with d-glucose displayed increased thickness, greater porosity, and higher hydrophilicity. Conversely, mycelium grown in PDB rich in lignin exhibited denser growth, faster development, and hydrophobic characteristics. Despite the differences, all mycelium samples had high water contact angles and resisted high temperatures. The authors conclude that mycelium-based materials offer a unique set of tunable properties that can be tailored to suit various applications [33].

An additional research effort examines the efficacy of mycelium-based composites (MBC) as an eco-friendly and biodegradable substitute for traditional insulation materials. The researchers utilize different substrates to cultivate MBCs and assess their physical attributes, including density, water absorption, thermal conductivity, and mechanical strength. Additionally, they analyze the hygrothermal performance of MBCs through accelerated aging experiments and tests measuring moisture buffer capacity. The results show that MBC has low thermal conductivity (0.057–0.085 $W \cdot m^{-1} K^{-1}$), high mechanical strength (0.145–0.452 MPa), low density (156–373 Kg/m^3), and good moisture buffer capacity of 1.632 $g/m^2 \cdot \%RH$. The authors' findings suggest that mycelium-based composites (MBCs) have potential applications as insulation materials within interior walls and integral components of building envelope systems designed for vapor permeability [34]. The production of mycelium-derived composites from spent mushroom substrate (SMS) and sawdust (SD) is a promising way to recycle lignocellulosic by-products and create eco-friendly materials. The growth and binding capabilities of two fungi, *Ganoderma lucidum*, and *Trametes versicolor*, were examined across various substrates. The results showed that T. versicolor could grow on both SMS and SD, while G. lucidum could only grow on SD. Both fungi generated lightweight substances exhibiting reduced thermal conductivity compared to traditional insulation materials [21]. An additional research endeavor investigates the creation of bio-composites using rice husks and sawdust, employing *Pleurotus ostreatus* fungus as a binding agent for insulation, packaging, and construction applications. The authors employ a Box-Behnken experimental approach to enhance the bio-composites' attributes by optimizing substrate type, water content, and incubation time. They then compare anticipated values for the physical, mechanical, thermal, and fire safety properties of the bio-composites. The outcomes reveal that the bio-composites are lightweight, porous, hydrophilic, moderately robust, rigid, thermally insulative, and capable of self-extinguishing [35].

An investigation delves into using fungal mycelium as a natural bonding agent for crafting biodegradable composite materials using wood sawdust. The researchers analyze and contrast the material properties of composites originating from the two fungi in their pressed and unpressed forms. They find that hot pressing affects the composites' morphology, hydrophobicity, and mechanical properties in different ways depending on the fungal species. They observe that T. versicolor produces a homogeneous layer of aerial hyphae that melts during hot pressing. At the same time, T. pubescent creates a more heterogeneous network of hyphae that retains its structure after hot pressing. They also measure the composites' water contact angle, density, porosity, thermal conductivity, and compressive strength. They report that both fungi produce strongly hydrophobic mycelium composites, with T. versicolor being more hydrophobic than T. pubescent. They also find that hot pressing reduces the composites' density, porosity, and thermal conductivity while increasing their compressive strength. They deduce that the mechanical attributes of mycelium composites subjected to hot pressing are on par with, or potentially exceed, those of Expanded Polystyrene [23].

Another research investigates the mechanical and morphological properties of biofoams produced from Oyster mushrooms and biomass substrates, namely sawdust and teak leaves. The paper aims to find a way to utilize agricultural waste and mushroom production to create biodegradable material. The paper uses two types of spawn: *Pleurotus sajor-caju* (Grey Oyster mushroom) and *Pleurotus djamor* (Pink Oyster mushroom) to inoculate the substrates and grow the biofoam. The paper tests the hardness, springiness, water adsorption, and morphology of the biofoam using scanning electron microscopy (SEM). The paper finds that teak leaves biofoam is more springy but less complicated than sawdust biofoam and that teak leaves biofoam has less water absorption than sawdust biofoam. The paper also observes that teak leaves biofoam has a dense filamentous and tubular structure, while sawdust biofoam has a more porous structure [36].

A research paper assesses the viability of utilizing mycelium as an alternative material for the sustainable construction industry. Mycelium can manufacture bricks and composites employing diverse substrates like rice bran, coconut husk, and sawdust. The study investigates the mechanical attributes of mycelium-based bricks and composites, focusing on properties such as density, thermal insulation, ductility, and fire resistance. The paper also discusses the production methodology of mycelium and the challenges involved. The study's findings suggest that mycelium-based composites exhibit reduced thermal conductivity compared to traditional materials, signifying favorable thermal insulation characteristics [37]. The study explores the potential of using the Material Driven Design (MDD) method to discover innovative and meaningful ways to utilize Mycelium-based Materials, leveraging their unique technical and experiential attributes. The article follows a master's student in product design on their journey using the MDD approach to create a concept for a lampshade that evolves over time, changing its appearance and function. Furthermore, the paper discusses the challenges and opportunities of designing with living materials, such as uncertainty, temporality, and acceptance, exemplified through the case study of a lampshade concept that evolves and changes its appearance and function [38].

5. Conventional Insulation Materials

In recent decades, thermal insulation of the exterior walls of buildings has become an imperative factor in reducing the building's energy demand caused by temperature differences between the exterior and interior [39]. Various conventional insulation types for building applications are proliferating, providing thermal and acoustic insulation to buildings (Figure 5). These materials can be categorized into two groups based on their composition: organic and inorganic. Each category has unique characteristics, advantages, and disadvantages, determining its suitability for specific applications.

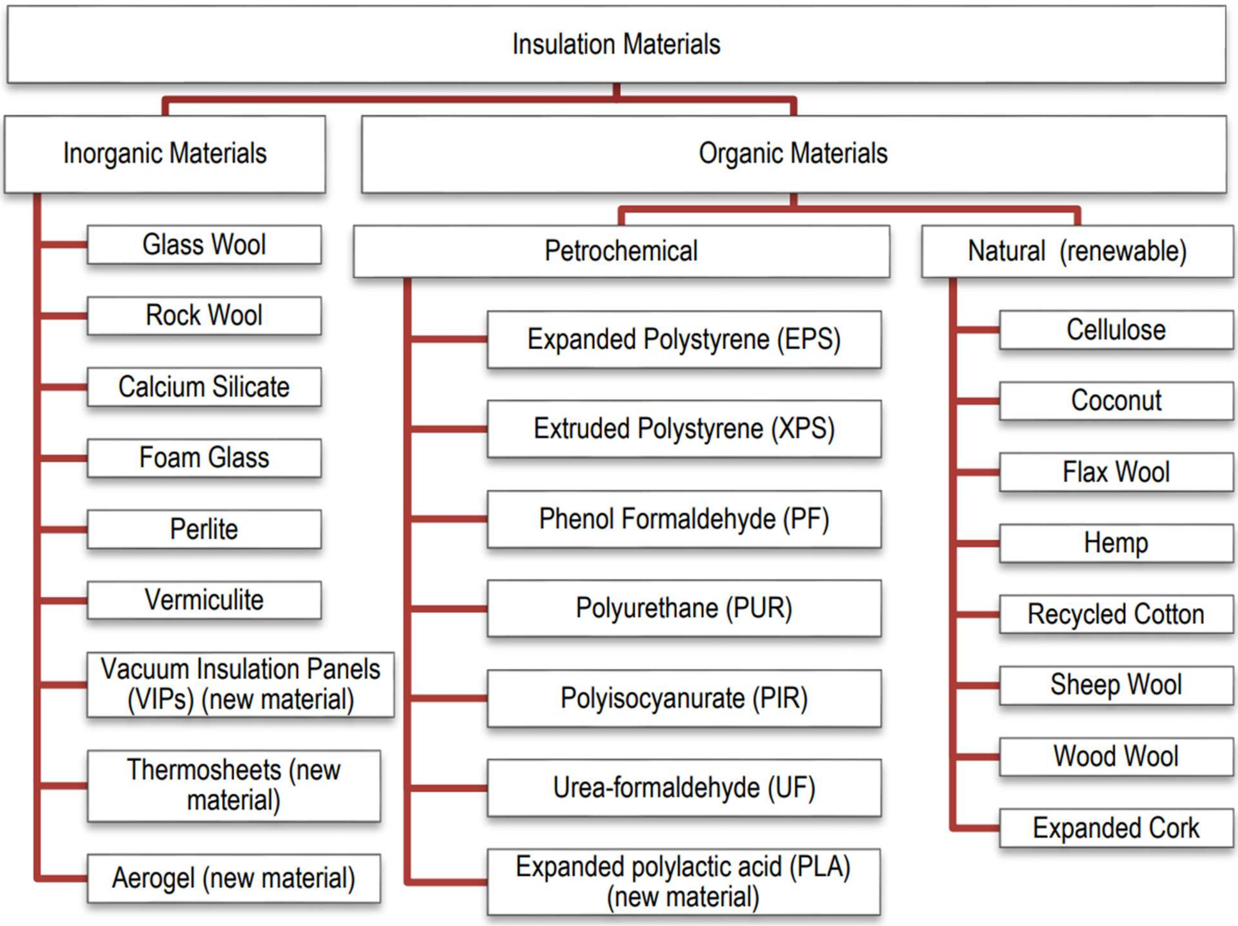

Figure 5. Classification of building insulation materials [40].

5.1. Inorganic Insulation Material

Inorganic materials are widely recognized and utilized as traditional insulation materials in residential buildings. These materials include glass wool, rock wool, calcium silicate, foam glass, perlite, vacuum insulation panels, thermos sheets, aerogel, and vermiculite. They have been extensively employed due to their thermal insulation and fire resistance properties, making them suitable for achieving efficient thermal insulation and ensuring enhanced safety in building environments [41].

5.1.1. Inorganic Fibrous Insulation Materials

In residential buildings, there has been a growing adoption of inorganic fibrous insulation materials due to their outstanding thermal efficiency, resistance to fire, and extended lifespan. These materials are fabricated using mineral or metal fibers, like glass wool and rock wool. They find widespread application as thermal insulators in diverse contexts, encompassing interior and exterior walls, roofs, foundations, cavity walls, unheated garages, band joists, storm windows, seals around windows and doors, and heating and/or cooling systems. Furthermore, these materials can be utilized as synthetic planar materials, low-density objects, or semi-structural materials, providing versatility and adaptability in building design [42]. Producing mineral wool insulators requires high temperatures to melt and fiberize the raw materials. Borosilicate glass is melted at around 1300 °C and spun into glass fibers, while rock is melted at about 1500 °C and formed into rock wool on a spinning wheel. This process consumes more energy than some other insulation materials [43].

5.1.2. Inorganic Cellular Insulation Materials

Inorganic cellular insulation materials are highly effective thermal insulation materials typically composed of natural or synthetic minerals. These materials are characterized by their cellular structure, consisting of many small air pockets that reduce heat transfer. In addition to their outstanding thermal properties, inorganic cellular insulation materials possess desirable attributes such as non-combustibility, moisture resistance, and durability. The foundational components in fabricating these materials include chalk, sand, cellulose fibers, cullet, dolomite, aluminum and silicon oxides, and magnesium-aluminum silicate. Noteworthy inorganic cellular insulation materials include calcium silicate, foam glass, perlite, and vermiculite. Due to their exceptional performance and versatility, these materials are widely utilized in various industrial and commercial applications where high-temperature resistance and fire protection are required [44].

5.1.3. Vacuum Insulation Panels (VIPs)

Vacuum insulation panels (VIPs) are a type of insulation material that consists of a rigid core with a microporous structure, such as silica, glass fiber, or polymer, that is evacuated and sealed in a thin, gas-tight envelope, such as aluminum foil or metalized film [45]. VIPs exhibit an exceedingly low thermal conductivity, typically averaging 0.004 W/m·K, due to the elimination of gas conduction and convection in the core. VIPs can provide high thermal performance with minimal thickness, making them suitable for applications where space is limited or valuable, such as building envelopes, refrigerators, and cryogenic tanks. However, VIPs also have some limitations, such as the risk of gas permeation through the envelope, the sensitivity to mechanical damage and puncture, the difficulty of cutting and shaping to fit complex geometries, and the high cost compared to conventional insulation materials. Therefore, VIPs require careful design, installation, and maintenance to ensure durability and effectiveness [46].

5.1.4. Thermoplastic Sheets

Thermoplastic sheets are plastic materials that can be heated and molded into various shapes and forms. They comprise polymers with different properties and characteristics depending on their chemical structure and composition. Thermoplastic sheets have some advantages, such as transparency, flexibility, durability, and recyclability. However, they also have some drawbacks, such as low resistance to heat and chemicals, high flammability, and environmental impact [47].

5.1.5. Aerogel

Aerogel is a solid substance characterized by substantial porosity, reduced density, and minimal thermal conductivity. It is composed of a network of nanosized particles and pores that are filled with gas. Aerogel was first prepared by Kistler in 1932 using a sol–gel method and supercritical drying [48]. Aerogel can be made from various sources, such as silica, alumina, carbon, organic polymers, and biopolymers. Aerogel holds significant promise for diverse sectors, including catalysis, radiation detection, and adsorption. However, due to its extremely low thermal conductivity, thermal insulation is one of the most prominent applications of aerogel. For example, silica aerogel has a thermal conductivity of about 12 mW/(m·K), much lower than conventional insulation materials. However, aerogel has limitations, such as brittleness, fragility, high cost, and moisture sensitivity [49].

5.2. Organic Insulation Material

Organic insulation materials can be classified into two categories: petrochemical and renewable. Petrochemical materials, such as expanded polystyrene (EPS), extruded polystyrene (XPS), phenol formaldehyde, polyurethane, polyisocyanurate, and urea formaldehyde, are widely used in conventional insulation systems. These materials are derived from oil or coal and have good thermal insulation properties but pose environmental and health risks. Renewable materials, such as cellulose, coconut, flax wool, hemp, recycled cotton, sheep wool, wood wool, and expanded cork, offer an eco-friendlier alternative for insulation. These materials are derived from plant or animal sources and have lower environmental impacts, such as carbon sequestration, moisture regulation, and biodegradability. Compared to traditional insulation materials, organic insulation materials require reduced energy input during manufacturing and exhibit a lower embodied energy.

5.2.1. Petrochemical Insulation Material

Polystyrene

Polystyrene is derived from styrene, an aromatic hydrocarbon obtained by reacting ethylene with benzene in aluminum chloride. Styrene is then polymerized using free-radical initiators to form polystyrene, a synthetic polymer with the chemical formula $(C8H8)_n$. Polystyrene can be solid or foamed and can be copolymerized or blended with other polymers to produce different types of products [50], such as solid plastic which includes general-purpose polystyrene (GPPS) and high-impact polystyrene (HIPS). GPPS is clear, hard, and brittle, while HIPS is opaque, tough, and impact resistant. Both types are easy to process and have a variety of applications, such as packaging, containers, toys, and models [51]. Foam includes EPS and XPS. EPS is a lightweight, durable material with excellent thermal insulation. EPS is made from polystyrene beads that are expanded by steam and molded into blocks or boards. XPS is an insulation material made from plastic beads that are melted and extruded into a continuous foam sheet. XPS has a smooth surface and a closed-cell structure, making it resistant to water and moisture. Both types of foam have low thermal conductivity and are often used for insulating roofs, walls, floors, and foundations [51]. Film: This includes oriented polystyrene (OPS), a thin, transparent film that can be stretched or oriented in different directions. OPS has good clarity, stiffness, and strength and is often used for packaging food and other products [51].

Polyurethane

Polyurethane comprises a category of polymers formed by linking organic units through carbamate (urethane) connections. Polyurethane can be produced from a wide range of starting materials and has many different applications, including foams, varnishes, coatings, adhesives, electrical potting compounds, and fibers. As a common procedure, polyurethane is generated through the reaction between an isocyanate and a polyol compound. Isocyanate is a compound that contains two isocyanate groups (-NCO), which can react with hydroxyl groups (-OH) from polyols. Polyols are compounds that contain multiple hydroxyl groups, such as glycols, polyesters, or polyethers [52]. It has high thermal insulation properties, which can reduce heat loss and carbon emissions. It also blocks air and moisture, acting as a barrier to leaks. It can be utilized in high-pressure or low-pressure foam and open-cell or closed-cell foam configurations. Polyurethane insulation's advantages are its versatility, light weight, durability, and easy installation. It can be used for various applications, such as roofs, walls, floors, and prefabricated panels. It can also be sprayed onto almost any surface, including complex interior spaces [53]. Some of the limitations of polyurethane insulation are its flammability and smoke emissions. Polyurethane can catch fire easily and produce toxic fumes when burned. Therefore, it needs to be protected by fire-resistant materials or coatings. Polyurethane may also degrade over time due to exposure to UV rays, moisture, or chemicals. Therefore, it needs to be inspected and maintained regularly. Polyurethane's environmental effects may stem from its reliance on fossil fuels and emissions of greenhouse gases during both its manufacturing and disposal processes [54].

Phenol Formaldehyde

Phenol-formaldehyde thermal insulation represents a category of insulating material crafted from synthetic polymers formed through the interaction of phenol or its derivatives with formaldehyde. Its production follows two techniques: one entails a direct reaction of phenol and formaldehyde to create a thermosetting network polymer, while the other method limits formaldehyde to generate a prepolymer called novolac. This prepolymer can be molded and subsequently solidified by adding additional formaldehyde and elevated temperatures. Phenol formaldehyde insulation has advantages such as thermal and chemical stability, adhesivity, high thermal insulation, and flame retardancy. However, it also has drawbacks, such as low mechanical performance, increased flammability, and limited availability. Some researchers have tried to improve the properties of phenol formaldehyde insulation by incorporating cardanol-based flame retardants or other additives [55].

Polyisocyanurate

Polyisocyanurate (PIR) is a type of thermal insulation produced as a rigid foam board or a foamed-in-place material. PIR is a thermoset plastic that is derived from the reaction of polyol and methylene diphenyl diisocyanate (MDI), with a higher proportion of MDI than polyurethane (PUR) [56]. The resulting polymer has a complex structure with isocyanurate rings and high cross-link density, which gives it superior thermal stability, chemical resistance, and mechanical strength. PIR also has a low flame/smoke rating and a low thermal drift, which means it retains its R-value over time. PIR is an ideal insulation material for energy-efficient and fire-safe buildings. Although PIR is a widely used thermal insulation material, it has some drawbacks that may limit its applicability and efficiency in certain situations. For instance, PIR can deteriorate under moist conditions, lose shape and integrity due to temperature changes, react adversely with some chemicals, perform poorly at very low temperatures, and cost more than other insulation options [57].

Urea-Formaldehyde

Urea-formaldehyde thermal insulation (UFFI) is a foam-insulating material that combines urea and formaldehyde. This non-transparent thermosetting resin or polymer possesses notable attributes, including high tensile strength, flexural modulus, heat-distortion temperature, and surface hardness. It also has low water absorption, mold shrinkage, and volume resistance. UFFI has been used for bonding particleboard, MDF, plywood, laminating adhesive, and thermal insulation in buildings [58]. UFFI has a thermal conductivity of 0.0343 to 0.0373 W/m·K, which can reduce heat loss and save energy. However, UFFI has some limitations, such as low compression strength, high pulverization rate, low limiting oxygen index, and possible formaldehyde gas emission during curing and aging. Therefore, UFFI has been banned or restricted in some countries due to health and safety concerns [59].

Polylactic Acid

Polylactic acid (PLA) is an environmentally degradable polymer from sustainable resources like corn starch or sugar cane. It is a thermoplastic material that can be processed by melt extrusion and compression molding. PLA is used as a thermal insulation material due to its low thermal conductivity, low density, and high compressive strength. It has a thermal conductivity of 0.0643 to 0.0904 W/m·K, depending on the degree of crystallization, which can be controlled by annealing. PLA also has a low water retention of less than 0.19%, which can resist moisture and mold growth. However, PLA also has some drawbacks as a thermal insulation material, such as poor heat resistance, a low glass transition temperature, a high pulverization rate, and a low limiting oxygen index. These properties make PLA susceptible to degradation and flammability at high temperatures [60].

5.2.2. Renewable Insulation Materials

Sustainable insulation materials can reduce buildings' energy consumption and environmental impact by providing thermal and acoustic insulation. They are usually made from natural, recycled, or renewable sources and have low embodied energy and greenhouse gas emissions.

Cellulose

Cellulose insulation is a type of home and commercial insulation made from any cellular plant source, usually recycled paper products such as newspapers, cardboard, office paper, etc. It is blown into the walls or attic of your home using a special machine that fluffs up the cellulose and shoots it through a hose. It can fit in enclosed areas and conform to pipes and ductwork within the space needing insulation [61]. It has low embodied energy and high recycled content, making it an eco-friendly choice for building insulation. Cellulose insulation can be applied as loose fill, sprayed into cavities and spaces, or as boards and mats for walls and roofs. However, cellulose insulation has some limitations, such as its high hygroscopicity, which can absorb moisture readily and cause mold growth, decay, and reduced thermal performance. Cellulose insulation may also settle over time and lose some thickness and effectiveness [62].

Cork

Cork insulation is a type of insulation made from cork material, which is harvested from the bark of cork oak trees. It is a natural, renewable, and recyclable product with high thermal resistance, sound isolation, fire resistance, and moisture resistance. It can be used for insulating walls, roofs, floors, and ceilings of buildings. It is available in different thicknesses and sizes, usually as boards or rolls. It is also hypoallergenic and toxins-free, making it a healthy choice for indoor environments [63]. Cork insulation has a typical thermal conductivity of 0.036 to 0.38 W/m·K, corresponding to an R-value of 3.6 per inch. However, cork insulation has some limitations, such as its high cost, low availability, and susceptibility to compression and shrinkage over time. Cork insulation may also not be suitable for very cold or hot climates, as it can handle temperature ranges of −292 °F to 248 °F [64].

Sheep Wool

Sheep wool insulation is a type of insulation that uses sheared wool from sheep as the base material. It is a natural, renewable, and biodegradable product used on roofs, walls, and floors to regulate temperature, minimize sound, and conserve energy indoors. Sheep wool insulation has some advantages over other types of insulation, such as its ability to manage moisture, improve indoor air quality, and absorb sound. However, sheep wool insulation also has some drawbacks, such as its higher cost, the need for additives to enhance its fire resistance and insect repellence, and its lower availability and ease of installation compared to other types of insulation [65–67].

Coconut

Coconut thermal insulation is a type of natural insulation that is made from coconut fibers, which are extracted from the husk of the coconut fruit. Coconut fibers have a low thermal conductivity of less than 0.04 W/m·K, which means they can prevent heat transfer and reduce energy consumption. Coconut fibers also have a low density of about 174 kg/m^3, a high heat capacity of 2600 J/kg·K, and a low water retention of less than 10%, which makes them suitable for thermal insulation in various climates. Coconut fibers can be used as loose-fill insulation in the cores of masonry walls or as mats or boards on concrete slabs' top or inner surfaces. However, coconut thermal insulation has some limitations, such as low compressive strength, high flammability, and possible degradation by microorganisms or insects [68–70].

Flax Wool

Flax wool insulation is a type of natural fiber insulation that is derived from the flax plant. It is a renewable and ecological material that can provide thermal and acoustic insulation for buildings. Flax wool insulation can be used as a replacement for petrochemical-based insulation. Flax fiber wool insulation is commonly manufactured into solid or partially solid rolls or as loose insulation materials. It requires treatment with a fire retardant, often accomplished using substances like ammonium salts or sodium borax. Flax wool insulation is part of a vapor-permeable system regulating relative humidity and providing a healthy indoor environment. Flax wool has a thermal conductivity of about 0.038 W/m·K, comparable to other natural fiber insulations such as hemp and sheep's wool. Flax wool is more expensive than mineral wool but has a lower energy demand in production and the potential for recycling [71].

Hemp

Hemp insulation, derived from natural hemp fibers, is an environmentally sustainable and biobased thermal insulation material that offers several advantages for enhancing buildings' energy efficiency and indoor air quality. One key benefit is its non-toxic, hypoallergenic nature and its resistance to mold and pests. Additionally, hemp insulation exhibits a high thermal resistance of 3.7 per inch and a low conductivity of 0.039 W/m·K, enabling effective thermal insulation. It also possesses excellent acoustic isolation properties, reducing noise in buildings. Furthermore, hemp insulation is user-friendly, easy to install, non-abrasive, and can be cut with various tools. However, it is essential to consider some limitations associated with hemp insulation, including its relatively higher cost than conventional materials like fiberglass or mineral wool. Moreover, some regions may need more availability and compatibility of hemp insulation with specific building codes or standards [72].

Recycled Insulation Materials

Recycled insulation materials are made from reused or reclaimed materials, such as plastic bottles, newspapers, glass, or denim. These materials are processed and transformed into insulation products used on roofs, walls, and floors to improve energy efficiency and comfort. They offer environmental and health benefits, such as lower energy use, lower carbon emissions, better indoor air quality, and good thermal and sound performance. However, they also have disadvantages, such as higher cost, lower availability, need for additives or treatments, and lower R-values or higher density than conventional insulation materials [73,74].

Wood Wool

Wood wool insulation is a natural and environmentally friendly product that combines fire resistance with outstanding acoustic and thermal performance. Produced from wood slivers obtained through log cutting, these slivers are mixed with a natural binding agent and additional additives, then compressed into boards that undergo dehydration in an oven. First, it is sourced from sustainably managed forests and adheres to the principles of complete recyclability following the 'cradle to cradle' approach. Moreover, its exceptional heat storage capacity enables it to maintain a comfortable indoor temperature during summer and winter. Additionally, it exhibits high vapor permeability and possesses excellent moisture-regulating capabilities, effectively preventing condensation and inhibiting mold growth. Its commendable sound-insulating properties reduce noise transmission between rooms or from external sources. Furthermore, it boasts easy installation, facilitating application between rafters or other beam structures. The availability of wood wool insulation in various surface textures, collars, and sizes allows for customization to meet diverse design requirements. However, it is essential to acknowledge the drawbacks of wood wool insulation. It tends to be more expensive than alternative insulation materials like mineral wool or cellulose. Additional fire protection or mold resistance treatments may be required depending on the additives utilized in the production process. Additionally, it may not be suitable for highly humid or wet environments, as it has the potential to absorb water and compromise its insulating properties. Therefore, when considering wood wool insulation for a specific application, it is crucial to evaluate its advantages and limitations [71].

6. Exploring the Promising Potential of Mycelium: A Sustainable Solution for Indoor Temperature Regulation, Particulate Matter Absorption, and Biodegradability

Mycelium is a promising natural insulation material that has shown great potential in achieving thermal comfort in buildings. Its high energy performance compared to traditional insulation materials makes it an ideal option for sustainable building insulation. Mycelium-based insulation provides a natural and sustainable solution that effectively regulates indoor temperatures, reducing the need for cooling systems. By maintaining consistent indoor temperatures, mycelium insulation helps to reduce energy consumption in buildings and consequently lowers the carbon footprint associated with cooling. This innovative material is highly versatile and can be used in different climate conditions, making it a viable solution for various building types and designs. Additionally, mycelium-based insulation is environmentally benign, making it a more sustainable and eco-friendly option than traditional insulation materials. A study presents a novel method of producing mycelium thermal insulation material by growing *Pleurotus ostreatus* on rye berries. To evaluate the impact of mycelium-composite bricks on building energy performance, the authors utilized the EnergyPlus software version 8.9.0 to simulate the heat and mass balance, building systems, and environmental conditions of various building types. They developed a typical residential building model consisting of one floor and four zones and implemented mycelium-composite bricks as the insulation layer in the external walls. Subsequently, the simulation results were compared with those of two conventional natural insulation materials: lightweight clay aggregate (LECA). They expanded vermiculite (EV), which has similar densities and thermal conductivities to the mycelium-composite bricks. This comparison was conducted for eight US climate zones, ranging from very hot to subarctic. The simulation results revealed several advantages of mycelium-composite bricks over LECA and EV in terms of building energy performance. Firstly, the mycelium-composite bricks reduced indoor temperature fluctuations by providing higher thermal inertia, allowing them to store more heat and release it slowly. This can enhance thermal comfort and decrease peak heating and cooling loads. Secondly, they reduced the total annual heating and cooling energy consumption by 5.6–18.8% and 1.9–13.6%, respectively, compared to LECA and EV. This can result in cost savings and conservation of energy resources for building owners and operators. Finally, mycelium-composite bricks reduced the total annual CO_2 emissions by 5.6% to 18.8% and 1.9% to 13.6%, respectively, compared to LECA and EV [20].

A study explores the potential of employing mycelium-composite panels as materials capable of adsorbing atmospheric particulate matter (PM). The researchers conducted a comparative analysis of PM adsorption effectiveness among four distinct mycelium composite types—hemp, rice straw, lacquer tree wood chips, and oak wood chips—as well as a conventional architectural material, Pocheon granite. Additionally, they investigate the surface micro-morphology of the panels using scanning electron microscopy and assess the panels' water absorption rate. The mycelium composites demonstrate notably improved PM adsorption capabilities compared to Pocheon granite, with variations in performance based on the substrate. The study also identifies a correlation between higher PM adsorption performance and elevated water absorption rates in the panels [12]. An additional research endeavor investigates the utilization of mycelium as an environmentally conscious substitute for air purification filters. The research introduces a computational model depicting an abstracted filter, varying pore sizes, and flow velocities and examines the interaction between pollutant particles and the mycelium's surface. The study aims to establish theoretical parameters that signify advantageous airflow patterns within the mycelium's structure and to deliberate upon the ecological advantages associated with employing mycelium as a filtering material. The paper also shows that the flow velocity affects the particle penetration depth and the possibility of filter clogging. The paper suggests that optimal pore size and flow velocity values can be determined for different pollutants and filter configurations. The paper concludes that mycelium has the potential as a biodegradable and renewable filter material that can effectively remove pollutants from the airflow [75].

Mycelium-Miscanthus composites as building insulation materials aim to develop a bio-based, biodegradable, self-growing material that can replace traditional insulation materials. The composite is made of Miscanthus x giganteus, a bioenergy crop, and Mycelium, which has a low density, low thermal conductivity, high fire safety, and a water-repellent fungal skin. The Miscanthus x giganteus composite can filter up to 30 metric tons of CO_2 per hectare over one year [76]. Mycelium-based composites have been shown to have promising sound absorption properties due to their porous and fibrous structure, low density, and high surface area. Mycelium-based composites can be used as acoustic insulation materials that can reduce noise levels and reverberation times in indoor environments. To create aesthetic and functional acoustic elements, they can also be shaped into various forms and designs, such as panels, tiles, or modules. Mycelium-based composites can achieve high sound absorption coefficients, which measure the fraction of sound energy absorbed by the material. For example, a study found that mycelium-based composites grown on agricultural plant-based residues had an average sound absorption coefficient of 0.36 and 0.42, comparable to commercial sound-absorbing materials [77]. Therefore, mycelium-based composites are a promising alternative for sound absorption materials that can enhance indoor spaces' acoustic quality and sustainability.

7. Environmental Impact of Mycelium Thermal Insulation

Mycelium insulation represents an innovative biomaterial achieved by cultivating fungal hyphae on organic substrates, notably agricultural and forestry residues. Diverging from conventional insulation materials like mineral wool, expanded polystyrene, and polyurethane foam, which stem from non-renewable resources and exhibit resistance to biodegradation, mycelium insulation distinguishes itself by its complete biodegradability. Integrating biodegradable materials holds the potential to curtail the environmental repercussions linked to waste generation and disposal while fostering nutrient cycling and enhancing soil vitality. Findings indicate that mycelium, functioning as a binding agent, displays an inclination towards initial decomposition. Evidently, a notable mass reduction of 43% was observed in inert samples comprising *Ganoderma resinaceum* fungal strain and hemp fibers after sixteen weeks. Nonetheless, the pace of disintegration in this context hinged upon a constellation of factors encompassing material constitution, manufacturing technique, and the intricacies of the degradation process, including equipment, materials, and environmental attributes. Noteworthy research affirms that mycelium insulation can undergo degradation within weeks or months, given favorable circumstances [78]. In contrast, conventional insulation materials tend to endure within the ecosystem for extended periods, amassing in landfills and aquatic habitats, thereby precipitating ecological harm. Furthermore, select conventional materials may contain deleterious components, such as formaldehyde, brominated flame retardants, or hydrofluorocarbons, which can leach into soil or water, thereby posing hazards to human health and wildlife. Consequently, mycelium insulation emerges as a viable, circular, and ecologically responsible alternative to existing insulation materials, underpinned by its profound biodegradability. Moreover, mycelium insulation engenders a pivotal avenue for carbon sequestration, wherein atmospheric carbon is assimilated and stored within its biomass, thereby ameliorating greenhouse gas emissions. A substantive proportion of terrestrial carbon, constituting 75%, is sequestered subterraneously. On a global scale, plant communities allocate 3.93 Gt CO_2e annually to arbuscular mycorrhizal fungi, 9.07 Gt CO_2e to ectomycorrhizal fungi, and 0.12 Gt CO_2e to ericoid mycorrhizal fungi. Based on this assessment, a notable 13.12 Gt of CO_2e sourced from terrestrial vegetation is temporarily attributed to the subterranean mycelium of mycorrhizal fungi each year, constituting a significant 36% of ongoing annual CO_2 emissions derived from fossil fuel sources [79].

The mycelium insulation material demonstrates notably reduced embodied emission values compared to other evaluated materials. When considering CO_2 absorption, mycelium insulation material's initial represented emission value stands at −244 $kgCO_2eq/m^3$. With decreasing energy requisites, these embodied emissions are further diminished to −298 $kgCO_2eq/m^3$, establishing the mycelium insulation material as carbon negative. Conversely, the displayed emission values for EPS, XPS, Polyurethane, and Phenolic foam are 231.2 $kgCO_2eq/m^3$, 271.8 $kgCO_2eq/m^3$, 560.5 $kgCO_2eq/m^3$, and 1136 $kgCO_2eq/m^3$, respectively. Illustrated in Figure 6, the mycelium insulation material boasts the most minor emissions per cubic meter of material, consequently yielding the most minimal cumulative emission value during the production process.

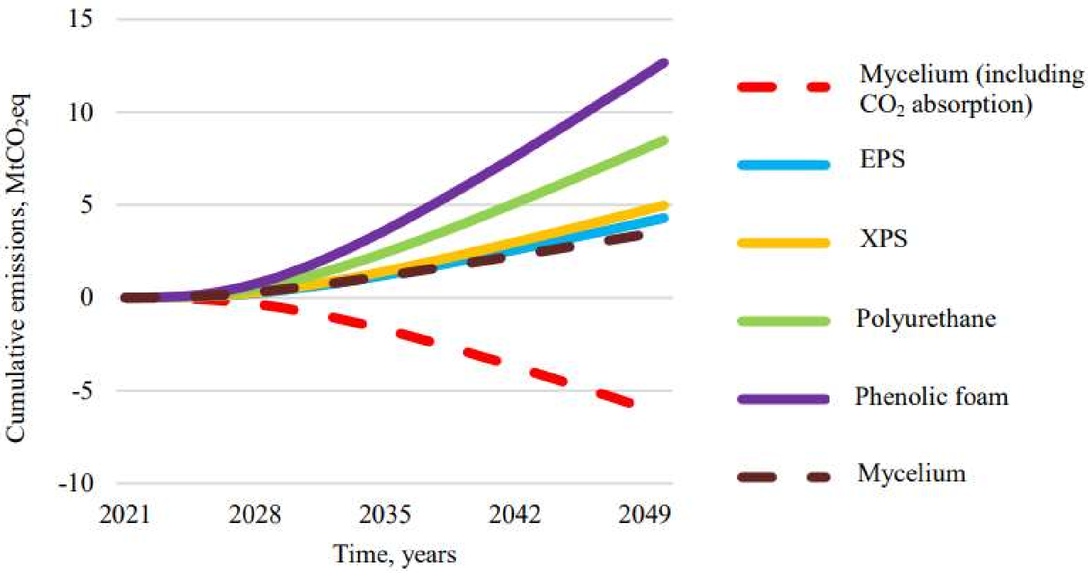

Figure 6. Accumulated GHG emissions throughout insulation material manufacturing [80].

8. Discussion

The drive for sustainable and energy-efficient building practices has led to a heightened exploration of innovative insulation materials capable of reducing residential cooling impacts. At the core of this endeavor lies the recognition that thermal conductivity profoundly influences insulation effectiveness. A comprehensive examination of existing literature illuminates the promise held by mycelium-based thermal insulation, showcasing notable thermal conductivity values ranging from 0.03 to 0.081 W/m·K [18–25,81]. Remarkably, these values align with and sometimes exceed those of commercially available traditional insulation materials. Comparatively evaluating mycelium-based insulation against conventional insulation materials assures its viability as an eco-conscious alternative. When compared with commercial insulation materials such as glass fiber (0.03–0.04 W/m·K) [82], mineral wool (0.03–0.04 W/m·K) [83], expanded polystyrene (0.036–0.054 W/m·K) [83], extruded polystyrene (0.034–0.044 W/m·K) [83], cellulose (0.04–0.066 W/m·K) [83], cork (0.04–0.05 W/m·K) [83], and polyurethane (0.02–0.03 W/m·K) [83], mycelium-based insulation emerges as a competitive thermal performer, often positioned within the lower end of the thermal conductivity range. This parity in thermal conductivity confirms the potential of mycelium-based insulation as a technologically advanced counterpart to conventional materials, thereby supporting its integration within sustainable architectural frameworks. Beyond thermal conductivity, insulation efficacy encompasses the concept of specific heat capacity. Within this context, mycelium-based insulation exhibits a distinct characteristic with specific heat capacity values ranging from 7.4 to 10.2 kJ/kg·K [81]. This particular feature positions mycelium-based insulation in sharp contrast to its established commercial counterparts. While glass fiber and mineral wool exhibit specific heat capacities of 0.8 kJ/kg·K [84,85] and expanded polystyrene registers 1.5 kJ/kg·K [86], mycelium-based insulation stands out due to its elevated specific heat capacity. Even when compared to polyurethane, characterized by specific heat capacities spanning 0.2359 to 0.2996 kJ/kg·K [87], mycelium-based insulation displays a noteworthy capability for heat energy storage. Mycelium, a natural and renewable material, holds promise as a thermal insulation material due to its low environmental impact and potential to replace conventional synthetic insulators. However, its suitability for thermal insulation in hot and arid environments presents notable limitations. The effectiveness of mycelium as a thermal insulator hinges on its ability to resist the transfer of heat, and its performance may vary based on specific environmental conditions, such as high temperatures and low humidity prevalent in hot and arid climates. The existing experiments have primarily focused on temperate environments, leaving a significant gap in understanding their behavior and efficiency under extreme heat conditions. To address this gap, there is a need for rigorous simulation studies that model the behavior of mycelium-based insulation in hot and arid climates. These simulations could incorporate factors such as temperature fluctuations, humidity levels, and solar radiation, enabling the estimation of its thermal performance and energy-saving potential in such challenging environments. By conducting virtual tests, researchers can forecast how much mycelium insulation can effectively reduce heat transfer, providing valuable insights into its viability for these specific regions. Moreover, these simulations can estimate the potential reduction in energy consumption and associated costs, thereby facilitating informed decision-making for architects, builders, and policymakers.

The adverse effects of noise pollution on human health, particularly for individuals residing and working in urban settings, have garnered significant attention within the context of architectural design and environmental sustainability [88]. Ensuring acoustic comfort within buildings is of paramount importance, necessitating the mitigation of external noise intrusion and the attainment of appropriate interior reverberation times. Research confirms the pivotal role of acoustically comfortable environments in fostering enhanced productivity, well-being, and overall occupant health. Mycelium composites demonstrate exceptional acoustic absorption properties owing to their inherent porous and fibrous structure. Notably, laboratory investigations have indicated an impressive acoustic absorption rate of approximately 75% at 1000 Hz, a frequency within the audible range of the human ear (20 Hz to 20 kHz) [89]. This magnitude of absorption aligns well with the frequencies commonly associated with road traffic noise, showcasing the potential of mycelium-based materials to mitigate such noise intrusions. Mycelium, lauded for its ecological merits, presents potential as an acoustic insulation material; however, its application in this context needs to be improved by several limitations. While mycelium exhibits favorable attributes, such as its lightweight nature and porosity, which can contribute to sound absorption, its effectiveness as an acoustic insulator remains largely unexplored. The need for comprehensive experimentation and comparative studies comparing mycelium with established acoustic insulation materials creates a substantial knowledge gap in understanding its acoustic performance. To address this gap, it is imperative to conduct thorough empirical assessments encompassing acoustic frequencies and environmental conditions. In the absence of comprehensive real-world installations, simulation emerges as a viable approach to assess mycelium's acoustic insulation potential. Advanced simulation tools can replicate various sound propagation scenarios and allow for the estimation of mycelium's sound absorption coefficients, transmission loss, and overall acoustic performance. Using simulations, researchers can quantify mycelium's capacity to mitigate sound transmission and evaluate its suitability for diverse settings, such as buildings. This approach also enables the exploration of optimal mycelium formulations and material densities to enhance its acoustic insulation properties.

A study highlights mycelium composites' economical and environmentally friendly nature compared to synthetic insulation materials. Notably, time to ignition (tig) is a critical parameter that characterizes the onset of flaming combustion and influences fire spread dynamics. The investigation reveals that mycelium composites cultivated on wheat grains and rice hulls exhibited comparable ignition times of 12 and 7 s, respectively, akin to those of XPS foam (9 s) but significantly shorter than particleboard (26 s). Furthermore, the decomposition of mycelium was observed to commence around 250 °C. The analysis of average heat release rate, a pivotal factor for predicting full-scale fire behavior, demonstrated that mycelium composites with wheat grains released marginally less heat (107 kW/m^2) compared to XPS foam (114 kW/m^2) and significantly lower heat than particleboard (134 kW/m^2). Moreover, the peak heat release rate, a critical parameter influencing maximum temperature and flame spread rate, was notably lower for rice hull-based mycelium composites (133 kW/m^2) in contrast to wheat grain-based mycelium composites (185 kW/m^2), synthetic XPS foam (200 kW/m^2), and particleboard (503 kW/m^2). In terms of environmental impact, mycelium composites demonstrated reduced emissions during combustion. The study revealed that mycelium composites emitted less smoke (0.9–70 m^2/m^2) and CO_2 (6.3–23.8 g) within 180 s from ignition compared to synthetic construction materials, which exhibited higher levels of smoke density (64–1184 m^2/m^2) and CO_2 release (15.2–29.9 g). Notably, mycelium composites derived from rice hulls displayed significantly lower CO_2 emissions (0.02 g) than synthetic samples (0.47 g) during the same time interval [31]. Further research supported the superior fire-retardant properties of mycelium composites, attributing their efficacy to substantial char formation, influenced by aromatic compounds and phosphorus in the mycelium, and the high silica content of agricultural waste used for growth. The overall findings of this review emphasize the potential of mycelium biocomposites as a promising green alternative for insulation materials. Using readily available agricultural waste contributes to their affordability and environmental suitability, while their biodegradability aligns them with circular economy principles [90,91].

A comparative study assessed the adsorption performance of mycelium composites cultivated on four distinct substrates (hemp, rice straw, lacquer tree wood chips, and oak wood chips) regarding particulate matter. These findings were juxtaposed against those of a prevalent architectural exterior material, namely Pocheon granite stone panels. The outcomes of isothermal calorimetry analysis indicate a marked increase in the adsorption capacity of nitrate and sulfate ions on the mycelium composite panels across all substrates, surpassing that of the Pocheon granite panels. Specifically, the mycelium panels exhibited notable variances in nitrate absorption, ranging from 204 mg/kg to 59 mg/kg, and sulfate absorption, ranging from 1189 mg/kg to 131 mg/kg. In contrast, the nitrate absorption capacity of Pocheon granite panels amounted to a mere 3 mg/kg, while sulfate absorption was measured at 4 mg/kg [12]. While existing research has shown promising results regarding the adsorption capacity of mycelium-composite panels for pollutants like nitrates and sulfates, there may be a limited understanding of how these panels perform over extended periods when exposed to various environmental factors such as weathering, temperature fluctuations, humidity, and other potential stressors. Investigating the long-term stability and performance of mycelium-composite panels in outdoor settings and their ability to maintain their adsorption capacity over time could provide valuable insights into their practical applicability as sustainable solutions for air quality improvement. This would involve conducting field studies and monitoring the panels' performance over several seasons to assess their durability, potential degradation, and ongoing adsorption efficiency.

Mycelium can capture and store carbon dioxide, a significant greenhouse gas contributing to global climate change. This natural process, called carbon sequestration, mirrors how plants and other organisms perform photosynthesis. Integrating living substances into construction and infrastructure can effectively transform them into carbon sinks, thereby reducing atmospheric CO_2 levels. Besides their carbon sequestration abilities, living materials also offer the potential to curtail energy consumption within buildings. For instance, insulation derived from mycelium has demonstrated impressive thermal insulation qualities, thereby diminishing the demand for energy-intensive heating and cooling systems. The application of mycelium in construction also carries the possibility of waste reduction and fostering a circular economy. Numerous living materials can be cultivated into specific shapes and sizes, minimizing the need for cutting and minimizing waste during the building process. Additionally, these materials can often be composted or recycled at the end of their life cycle, reducing the waste volume directed to landfills. Despite their manifold advantages, the widespread adoption of living materials is accompanied by challenges. A key hurdle is the need for standardized testing and certification protocols for these materials, preventing architects and builders from confidently integrating them into their projects. Furthermore, producing and utilizing living materials may necessitate new skills and expertise, warranting investments in education and training [92].

Mycelium insulation panels exhibit certain limitations. Despite being deemed "durable" by some due to their bio-based and compostable nature, these materials do not possess lasting longevity. Over time, mycelium materials tend to shrink, becoming susceptible to contamination by other organisms or insects when dried and often developing surface cracks upon dehydration. The absence of a protective coating further leads to their deterioration and discoloration [93]. Although a separate study indicated the potential for a lifespan of roughly 20 years under stable conditions, this claim needs more rigorous scientific backing, relying instead on empirical observations during experimental endeavors [94]. Consequently, substantial research remains imperative to ascertain the viability of mycelium materials as practical and enduring products, especially given the current dearth of knowledge concerning their long-term sustainability, life cycle, and eventual degradation. Furthermore, mycelium insulation panels exhibit heterogeneity in their composition. Effectively controlling their mechanical attributes poses a challenge, given that their consistency is contingent upon the biological diversity of the organism and the specific biowaste feedstock utilized, leading to inherent fluctuations in their mechanical properties. The fabrication of mycelium materials necessitates a dual set of specialized requirements. On the one hand, it demands a controlled laboratory environment with stringent sterility protocols and precisely regulated growth chambers. On the other hand, it entails the utilization of specific equipment such as heat-press machines, advanced coating techniques, and convection ovens. While the procedural framework prevalent in biotechnological advancements, notably in fermentation processes, is well-established, it remains uncharted mainly within the domain of construction material innovations, particularly in composites. However, the convergence of these distinct realms becomes imperative for successfully developing bio-fabricated materials of this nature [93].

Tables 2 and 3 summarize the main differences between mycelium and conventional insulation materials, as depicted in this review.

Table 2. Thermo-physical, Cost, Water Absorption, and Durability Properties.

Material	Specific Heat (kJ/kg·K)	Density kg m^{-3}	Thermal Conductivity $(W\ m^{-1}K^{-1})$	Cost $(€/m^2)$	Durability (years)	Water Absorption Rate (%)	Ref.
Glass Wool	0.85	12–64	0.03–0.45	77.5–147	20–30	75	[40,95–99]
Rock Wool	0.7	20–64	0.03–0.040	102.08–179.5	30–50	N/A	[40,100–103]
Foam Glass	N/A	N/A	0.038–0.055	357.38–445.5	50–80	N/A	[40,104]
Perlite	0.9–1.0	30–400	0.040–0.055	207.89	50	N/A	[40,97,105,106]
Vermiculite	0.8–1.0	170	0.062–0.090	152.6	N/A	N/A	[40,97,107]
Aerogel	1.05	150–220	0.015–0.028	168.04	10	50	[97,108–110]
EPS	1.25	15–30	0.03–0.040	61.42–186.56	50	25	[40,97,111–113]
XPS	1.3–1.7	24–45	0.025–0.040	156–180	50	N/A	[40,97,114]
Polyurethane	1.3–1.45	31.5–35	0.021–0.040	303.78	30–50	30	[40,97,115,116]
Cellulose	1.3–2.0	30–80	0.035–0.042	175.71	20–30	60	[40,97,117–119]
Cork	1.5–1.7	80–115	0.035–0.050	N/A	50	N/A	[64,97]
Sheep wool	1.9–2.0	30	0.033–0.040	33.9	60–100	35	[40,97,120,121]
Flax	1.4–1.6	30–40	0.038–0.042	116.77	N/A	12.3	[40,97,122]
Hemp	1.6–1.7	38–41	0.039–0.06	108.1–138.93	N/A	20	[40,97,123]
Mycelium	7.4–10.2	51.098–1420	0.029–0.081	15.62–34.32	20	17.2–37.6	[21,26,27,124,125]

Table 3. Main differences between mycelium and other conventional thermal insulation materials.

Property	Mycelium	Other Conventional Materials	Comments
Specific Heat	x		Mycelium has higher specific heat than all other conventional materials
Density	x		Mycelium has a wide range of densities that suit different applications
Thermal conductivities	x	x	Both mycelium and other materials have comparative thermal conductivities
Cost	x		Mycelium has a much lower cost than most other conventional materials
Durability		x	Mycelium is, on average, less durable than most conventional materials
Water absorption rate	x	x	Both mycelium and other materials have acceptable water absorption properties

9. Conclusions and Future Research Recommendations

Mycelium is an emerging and promising choice of material for building envelope insulation. This paper highlights the potential of mycelium-based thermal insulation as a sustainable solution for reducing cooling energy consumption and carbon footprint in arid and hot climate regions compared to conventional and other emerging insulation materials. The heavy reliance on energy-intensive air conditioning systems in such areas and the need for more conventional insulation materials and craftsmanship necessitates exploring innovative approaches. Mycelium offers exceptional properties, making it an attractive thermal and acoustic insulation material. Its low thermal conductivity, water absorption coefficient, porous structure, and low density contribute to its excellent performance in regulating indoor temperature and improving energy efficiency. Furthermore, mycelium-based materials can absorb particulate matter from the air, enhancing indoor air quality and reducing air pollution.

This review emphasizes the multifaceted capabilities of mycelium in addressing critical environmental challenges. Its mechanical strength, low density, and porous structure make it a suitable material for insulation applications, while its ability to filter airborne particles contributes to improved indoor air quality. Moreover, mycelium's chemical properties enable it to play a role in bioremediation by actively degrading pollutants in soil and water. Buildings account for significant global energy consumption and carbon dioxide emissions. By effectively utilizing insulation materials with enhanced properties, such as mycelium-based composites, the heat load on buildings can be reduced, leading to lower energy consumption, and increased overall energy efficiency. However, several important aspects still need further investigation to make mycelium a cost- and application-competitive material. Firstly, more comprehensive studies are required to determine the cost implications of using mycelium as an insulator compared to traditional insulators. This includes the initial production costs and long-term maintenance and durability considerations. Additionally, assessing the environmental impact of mycelium insulation compared to conventional insulators is crucial for making informed decisions. Future research should focus on conducting life cycle assessments and analyzing the carbon footprint of mycelium-based insulation materials. Moreover, understanding the challenges and opportunities for growing and producing mycelium is essential for its successful implementation. Research should delve into several conditions, such as temperature, humidity, and the availability of suitable substrates, to optimize mycelium growth and production processes. Furthermore, investigating mycelium-based insulation's scalability and commercialization potential would be valuable for widespread adoption. In summary, while mycelium shows promise as a sustainable and widely available insulator, further research is needed to address its production's cost implications, environmental impact, and scalability. Investigating the challenges and opportunities for mycelium growth and production, along with exploring optimization strategies and alternative applications, will contribute to the advancement of mycelium as a cost- and application-competitive material in the construction industry.

This study has illuminated the promising potential of mycelium-based insulation materials as a sustainable solution. The research underscores mycelium composites' notable thermal advantages and eco-friendly attributes. However, it is essential to acknowledge the existing challenges in areas such as cost assessment, large-scale production, and quantifying carbon footprint reduction. Despite these gaps, architects and builders can explore mycelium as a viable alternative to conventional insulation, especially in arid contexts, considering the need for optimizing production processes and addressing scalability concerns. As the construction industry continues to navigate sustainable practices, the potential for mycelium-based insulation to contribute to reduced energy consumption and improved indoor comfort remains significant. The culmination of this research serves as a catalyst for ongoing collaborative efforts among researchers, practitioners, and stakeholders, driving the evolution of environmentally conscious construction methodologies in arid and hot climate regions.

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