Environmental and Climate Technologies
2025, vol. 29, no. 1, pp. 201–211
https://doi.org/10.2478/rtuect-2025-0014
https://content.sciendo.com

Development of a Mycelium-Based Thermal Insulation Material

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Received 19.03.2025; accepted 08.05.2025

Abstract **– The study explores the potential of mycelium-based materials as sustainable thermal insulation for construction. Mycelium, the vegetative part of fungi, grows on organic substrates such as agricultural byproducts, forming a lightweight, biodegradable composite with insulating properties. The experiments focus on optimizing the material's thermal conductivity and mechanical strength. Mycelium insulation demonstrates thermal conductivity values comparable to traditional materials like mineral wool and expanded polystyrene (EPS), with a range of 0.039 to 0.05 W/m·K. The production process employs renewable resources, is non-toxic, and aligns with circular economy principles by repurposing agricultural waste. Challenges remain in enhancing water resistance and mechanical adaptability. The findings underline mycelium's potential as an eco-friendly alternative in modern sustainable construction, emphasizing its role in reducing carbon footprints and promoting resource efficiency.**

Keywords **– Agricultural by-product; eco-friendly materials; mycelium; thermal insulation.**

1. INTRODUCTION

The demand for sustainable thermal insulation materials and the reduction of environmental pollution are among the greatest challenges of the 21st century. Achieving sustainability in energy and environmental sectors is critical, as energy consumption continues to outpace limited resources, while growing populations and premature material disposal exacerbate environmental concerns [1].

The construction and automotive industries are among the largest energy consumers, with buildings alone accounting for approximately 40 % of global energy use and generating 36 % of total CO_2 emissions. Consequently, improving energy efficiency in buildings has become a priority. High-performance thermal insulation can significantly reduce heat loss during heating and cooling, with studies indicating that proper insulation can cut household energy consumption by up to 65 % [1].

As awareness of the environmental impact of building materials grows, new solutions are being developed to lower carbon emissions, reduce reliance on non-renewable resources, and enhance indoor air quality. This has led to an increasing focus on bio-based insulation materials such as wood fiber, hemp, and straw [2]. Additionally, circular economy principles

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are being applied to promote the reuse and recycling of materials, reducing waste and environmental pollution [3].

One of the most promising bio-based insulation materials is mycelium – the vegetative part of fungi, which acts as a natural binder for organic substrates. This innovative technology allows the production of biodegradable, lightweight, and fire-resistant biocomposites. Mycelium biocomposites (MB) can be molded into various shapes, offering a sustainable alternative to synthetic materials like expanded polystyrene (EPS) while maintaining similar insulation properties and a lower environmental footprint [4].

Besides reducing CO_2 emissions and costs, mycelium-based insulation supports the circular economy, as confirmed by life cycle analysis [5]. However, MB insulation still faces challenges, including high density and water absorption, which hinder its commercial viability. Its performance depends on factors such as substrate composition, fungal strain, and incubation conditions, necessitating further research and design improvements [6].

Despite these challenges, MB materials open new possibilities for designers, including the creation of customized shapes through 3D printing. However, their production remains labor-intensive and requires automation and digital optimization. Advancements in material properties and manufacturing processes are essential to fully realize their potential. Addressing these limitations could make mycelium biocomposites a viable alternative to conventional insulation materials, significantly contributing to sustainability and the circular economy [7], [8].

2. LITERATURE REVIEW

In response to the increasing demand for sustainable materials, mycelium-based products have gained significant attention as an eco-friendly alternative. Their ability to replace traditional synthetic materials makes them particularly suitable for insulation and packaging applications.

Mycelium-based materials can be produced in two ways:

- By utilizing mycelium's natural ability to bind to various substrates, forming a dense and durable structure.
- By cultivating pure mycelium from liquid cultures [9].

The performance of mycelium-based materials is heavily influenced by cultivation methods, similar to how material science and engineering emphasize the relationship between structure, properties, and processing conditions. Key factors such as humidity, temperature, and substrate composition play a crucial role in determining material quality [10].

Research has primarily explored different substrates for mycelium cultivation, including:

- Agricultural waste [11],
- By-products from food processing [12],
- Industrial waste from paper and textile production [13].

Not all fungal species and substrates are equally effective for mycelial growth. The rate of colonization and material density vary depending on substrate type and environmental conditions [10].

The choice of substrate is essential, as it directly impacts mycelial growth and the quality of the resulting green composites. Several chemical factors must be considered when selecting a substrate, including cellulose, hemicellulose, and lignin content, pH level, organic carbon, total nitrogen, and the carbon-to-nitrogen (C:N) ratio. These factors influence not only the efficiency of mycelial growth but also the properties of the final product [14].

Cellulose, a key component of plant cell walls, serves as an important carbon source for mycelium, providing essential nutrients that support robust growth and the formation of durable composite materials. Hemicellulose, another plant cell wall component, also contributes to mycelial growth and enhances the mechanical properties of the final product. In contrast, lignin, a complex polymer that reinforces plant cell walls, is more challenging for mycelium to break down, making substrates with lower lignin content more suitable for cultivation. Additionally, mycelium thrives best in slightly acidic conditions (pH 5–8), necessitating careful pH adjustments for optimal growth [15].

Organic carbon serves as a primary energy source for mycelium, promoting vigorous growth. Similarly, nitrogen is essential for protein synthesis, enzyme production, and cellular processes. An optimal C:N ratio, typically ranging from 19:1 to 80:1, is crucial for balanced mycelium development. Substrates with a higher C:N ratio may require additional nitrogen supplementation. Overall, selecting an appropriate substrate is a critical step in optimizing the production of high-quality mycelium-based composites [14].

Temperature and humidity also play significant roles in mycelial growth. The ideal temperature is around 24–25 °C [16], [17], while high humidity levels (up to 98 % relative humidity) are required to support mycelial development. Consequently, humidifiers are often used to maintain appropriate growing conditions [17], [18].

Once the mycelium has fully developed, it contains a high water content (over 60 %). To halt further growth and ensure reliable mechanical properties, most of this moisture must be removed. For example, hemp pulp-based substrates retain more water than cotton wool. Additionally, various coatings can influence moisture absorption. The moisture content before inactivation typically ranges between 59 % and 70–80 %, with the final material retaining approximately 10–15 % moisture, as recommended by researchers [17].

To produce mycelium-based materials, it is crucial to focus on developing a robust mycelial network while minimizing energy-intensive fruiting body formation. The mycelium cultivation process consists of four main steps, with three additional steps required for material production [19].

First, the substrate is prepared, providing the necessary environment for fungal growth. The substrate can include cellulose-rich materials such as straw, wood, or hemp, chosen based on the species of mycelium and cultivation goals [20]. For large-scale production, cost-effective and nutrient-rich substrates like straw are preferred. Conversely, laboratory research often employs pure and easily controlled substrates, such as sugar solutions. Following preparation, the substrate undergoes sterilization to eliminate competing microorganisms [21]. Next, the sterilized substrate is inoculated with mushroom spawn, which is typically sourced from specialized facilities that maintain high purity standards. Mycelium then colonizes the substrate, forming a uniform material. Throughout this phase, precise environmental control is necessary, depending on the fungal species and production objectives. Once the substrate is fully colonized, growth is halted to prevent further metabolic activity that could compromise material integrity [22]. This is achieved through heat treatment, which terminates mycelium development. Finally, the material is removed from its mold and may be coated with protective layers to enhance its mechanical strength and aesthetic appeal. The resulting mycelium-based composites offer a sustainable alternative to traditional materials while maintaining high quality and adaptability for various industries [23].

Thermal insulation materials are typically evaluated based on their thermal conductivity coefficient, λ, which ranges from 0.024 to 0.07 W/m·K. The effectiveness of insulation materials – whether homogeneous, simple, or composite – is assessed using parameters such as thermal conductivity, heat transfer rate, thermal diffusivity, and specific heat capacity. For commonly used insulation materials, the thermal conductivity coefficient ranges from 0.030 to 0.040 W/m·K for expanded polystyrene and mineral wool, and from 0.020 to 0.030 W/m·K for polyurethane-based insulation. Mycelium-based insulation materials, with their sustainable composition, offer a promising alternative within this range [24].

3. METHODOLOGY

For the production of mycelium materials, agricultural by-products such as straw and wood chips were used, which served as a substrate for mycelium growth. The experimental process for developing mycelium-based insulation material began with screening nine mold species to identify the most suitable candidate for material production. These included *Rhizopus oryzae*, *Aspergillus versicolor*, *Penicillium chrysogenum*, *Cladosporium cladosporioides*, *Cladosporium herbarum*, *Stachybotrys chartarum*, *Trichoderma viride*, *Mucor mucedo*, and *Mucor plumbeus*. The primary selection criteria were the formation of a dense hyphal network and rapid growth rate. Cultures were initially grown on two nutrient media: Potato Dextrose Agar (PDA) and Malt Extract Agar (MEA). The choice of these materials was determined by their wide availability, low cost and richness of organic composition, which provides the nutrients necessary for mycelium growth. For additional stability and homogeneity of the substrate, a mixture of xanthan, water and ethanol was used as a binder. Although mycelium naturally acts as a binder, creating a cohesive and mechanically stable biocomposite, in some cases it is not enough to ensure uniform substrate distribution and structural homogeneity before mycelium colonization. Therefore, a mixture of xanthan and water is used as a structuring and moisture-retaining agent, which: 1) improves the plasticity of the substrate, 2) prevents the settling or separation of bulk particles, 3) and ensures uniform distribution of the mycelium. Xanthan is not used as a source of mechanical strength of the final material, but as an aid in the early stages of formation. The experimental part was carried out at the Riga Technical University's Institute of Energy Systems and Environment Laboratory, where appropriate conditions and control over the entire process were provided. The substrate preparation stage included the careful creation of a mixture of straw and wood chips, using different proportions according to the experimental plan. Precise dosing allowed to achieve the necessary homogeneity and ensured optimal distribution of nutrients. The prepared mixture was subjected to sterilization in an autoclave (temperature approximately 121 °C, pressure one atm) to destroy unwanted microorganisms and seeds that could interfere with mycelium growth. After sterilization, the substrate was cooled to room temperature to maintain favorable conditions for inoculation.

The sterilized substrate was inoculated with *Trichoderma viride* spores previously grown on potato dextrose agar (PDA) and enriched media. This fungal strain was selected due to its high growth capacity and efficiency in creating a dense mycelium network.

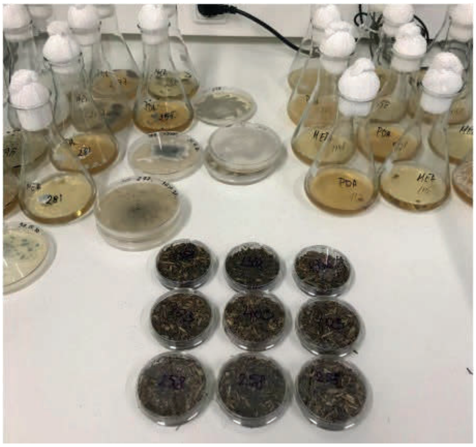

Fig. 1. Mycelium samples with a mass of 20 mg each.

3.1. Mycelium Material Production Process

3.1.1. Inoculation and growth

The inoculated substrate was placed in metal molds with dimensions of 20×20 cm, which provided a shape and structure for the growth process. Optimal growth conditions were maintained in the molds:

- Temperature: 25–30 °C,
- Relative humidity: 60–70 %,
- Substrate pH: ~5.

The growth process lasted 3–5 days, during which the mycelium actively colonized the substrate, forming a dense network that bound the substrate particles into a single material. The mycelium served as a natural binder, creating a mechanically stable structure.

Fig. 2. Mixing mycelial material.

3.1.2. Heat treatment

Once the growth process was complete, the molds with mycelium material were transferred to a heat treatment chamber. The material was subjected to drying at temperatures up to 105 °C to stop further mycelium development, prevent fruiting body formation, and destroy any remaining moisture sources. The heat treatment ensured the mechanical stability of the material, as well as reduced its thermal conductivity.

Fig. 3. Mycelium material after drying.

3.1.3. Testing and analysis of the finished material

After heat treatment, the mycelium material obtained was subjected to thorough testing using standard laboratory methods. The following measurements were taken:

- Thermal conductivity: Determined to assess the insulation properties of the material and compare it with traditional synthetic insulation materials.
- Density: Measured to assess the uniformity of the material and its suitability for various applications.
- Mechanical strength: Tested to determine the compressive and tensile properties of the material, which are essential in various industries, such as construction and design.

The study developed and analyzed a process that ensures efficient production of mycelium materials, from substrate preparation and inoculation to thermal treatment of the final product. The obtained samples were thoroughly tested to evaluate their physical and mechanical properties, which allows evaluating the material's potential in various fields of application. The results discussed below provide an insight into the main characteristics of the material.

4. RESULTS

More than 130 material samples (20×20 cm in size) were produced during the study. Various substrates were used, including straw, wood chips, hemp, hay, and their combinations. The mycelium was mixed with 13 different types of additives in various combinations, such as xanthan gum, glycerol, ethanol, gluten, yeast, molasses, baking soda, nutrient medium, water, starch solution, and sapropel. These combinations were tested to explore the effects of different ingredient ratios and interactions on the growth, structure, and properties of the resulting mycelium-based materials.

Mycelium composite materials were developed in the experiment, the properties of which were analyzed to determine their potential as an environmentally friendly and sustainable thermal insulation material. The study focused on the thermal conductivity, density, mechanical properties and ecological aspects of the materials.

4.1. Thermal Conductivity Analysis

When testing experimental samples of mycelium materials, their thermal conductivity values were in the range of 0.039–0.05 W/m·K. According to the literature, the thermal conductivity of mycelium thermal insulation materials is on average from 0.03 to 0.07 W/m·K [3]. These indicators are comparable to traditional thermal insulation materials, such as mineral wool and expanded polystyrene, which indicates the competitiveness of mycelium materials in the construction industry. Low thermal conductivity allows these materials to be used in the construction of more energy-efficient buildings, reducing energy consumption for heating and cooling.

TABLE 1. MATERIAL PROPERTIES

Material	Thermal conductivity (W/m·K)	Density (kg/m^3)
Plant-based		
Mycelium	0.039–0.05*	72–120*
Hemp	0.039–0.043 [25]	28–42 [25]
Flax	0.034–0.052 [26]	40–100 [26]
Rice husk	0.04–0.073 [27], [28]	97–200 [29]
Wood fiber	0.038–0.042 [30], [31]	50–250 [30], [31]
Inorganic (fibrous & foam)		
Glass wool	0.03–0.045 [32]	10–96 [32]
Rock wool	0.034–0.035 [33]	45–140 [33]
Synthetic foams		
EPS	0.035–0.037 [34], [35]	12–50 [34], [35]
Polyurethane	0.027–0.037 [36], [37]	88–111 [36], [37]
Phenolic foam	0.018–0.023 [38]	35–200 [38]
XPS	0.033–0.04 [39]	28–78 [39]

*The data are obtained experimentally.

4.2. Density Properties

The density of the mycelium materials ranged 72–120 kg/m³, and depended on the type of substrate used and the mycelium growth conditions:

- Higher densities (120 kg/m³) were achieved using substrates with a higher amount of wood chips.
- Lower densities (72 kg/m³) were observed using straw or hay as the main substrate components.

The possibility of varying the density ensures the adaptability of the material to different needs, such as lighter structures or higher mechanical strength.

4.3. Mechanical Properties and Stability

The experimental samples with higher densities showed higher mechanical stability, which is an essential property for the materials to be used in construction. They successfully withstood compressive loads and maintained their integrity after heat treatment and dehydration. At the same time, materials with lower densities offered better thermal insulation, however, their mechanical properties still need to be improved. Further research will focus on finding a balance between these two properties.

4.4. Ecological Aspects

Mycelium materials are biodegradable and are produced using renewable resources, such as agricultural by-products (straw, hay, wood chips). No toxic chemicals were used in the production process, making the materials safe for both humans and the environment. Their production ensures low carbon emissions and promotes the reuse of resources.

5. CONCLUSIONS

Experimentally developed mycelium materials demonstrate low thermal conductivity (0.039–0.05 W/m·K), making them comparable to traditional insulation materials such as mineral wool and expanded polystyrene. This confirms their potential as an alternative thermal insulation solution, particularly in light of the growing demand for environmentally friendly and energy-efficient construction methods. Their low thermal conductivity enhances building energy efficiency by reducing heating and cooling demands, thereby contributing to sustainable development.

The material's density ranges from 80 to 120 kg/m³, allowing for adaptability to various practical applications. A higher density provides greater mechanical stability, making it suitable for load-bearing structures, while a lower density improves thermal insulation and reduces weight—an important factor for lightweight constructions. Mycelium materials exhibit sufficient mechanical strength to withstand compressive loads, even after heat treatment and dehydration, making them a viable option for construction applications where both durability and sustainability are key considerations.

Produced from renewable resources such as agricultural by-products (straw, wood chips, hay), mycelium composites are manufactured without toxic chemicals, offering significant ecological benefits. Their biodegradability ensures natural decomposition, reducing construction waste and environmental impact. Additionally, their low ecological footprint results from resource reuse and minimal emissions during production, making them particularly attractive in sustainable construction.

Despite their promising properties, some challenges remain. The material's sensitivity to moisture necessitates improvements in water resistance, especially for applications in humid environments. Several solutions are being explored to improve water resistance. One of them is the use of biocompatible coatings – for example, layers based on biowax, natural resins or chitin, which reduce water absorption while maintaining the biodegradability of the material. Enhancing the mechanical properties of lower-density variants is also essential, as greater strength in lightweight materials could expand their usability across various industries. Ongoing research into optimizing substrate composition and growth conditions can help strike a balance between thermal insulation, mechanical stability, and density.

Mycelium composites present an innovative and sustainable solution for insulating residential buildings, where an eco-friendly and energy-efficient approach is required. They are also well-suited for lightweight structures, such as temporary buildings or interior panels, due to their low weight and ease of biodegradation after use. In industrial construction, they offer a viable alternative to conventional materials with enhanced sustainability. The wider adoption of mycelium materials in the future could reduce dependence on fossil-based resources, enhance construction sustainability, and support the transition to a circular economy.

ACKNOWLEDGMENT

This work has been supported by the EU Recovery and Resilience Facility within the Project No 5.2.1.1.i.0/2/24/I/CFLA/003 "Implementation of consolidation and management changes at Riga Technical University, Liepaja University, Rezekne Academy of Technology, Latvian Maritime Academy and Liepaja Maritime College for the progress towards excellence in higher education, science and innovation" academic career doctoral grant (ID 1093).

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