FABRICATION AND CHARACTERIZATION OF MYCELIUM-BASED BIO-COMPOSITE INSULATION FROM AGRICULTURAL WASTE

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Abstract

As the demand for sustainable building materials rises, bio-based insulation solutions are gaining attention. This study presents a novel thermal insulation material created by using mycelium as a natural binder, combined with agricultural waste as the substrate. Preliminary tests show that the mycelium-based bio-composite offers competitive thermal properties and demonstrates a lower environmental impact compared to conventional synthetic insulations. However, further research is required to fully assess its performance and potential applications.

Keywords

Bio-composite, mycelium, thermal insulation, natural sources

1 INTRODUCTION

Due to the negative impacts of synthetic materials in the construction industry, increasing emphasis is being placed on sustainability and the development of environmentally friendly building materials. Thermal insulation, which constitutes a significant portion of the building envelope, enhances the energy efficiency of building structures by reducing energy consumption during building operation. One alternative to synthetic thermal insulations are bio-composites, which are composed of natural materials and binders. Natural materials such as corn, hemp, sheep's wool, and straw are known for their thermal insulation properties and have historically served this function in buildings. Today, thermal insulation must meet stringent requirements in terms of thermal conductivity, moisture transfer, water absorption, mechanical strength, fire resistance, pest resistance etc. Therefore, selecting the appropriate components of a bio-composite is crucial to achieving the desired properties of construction materials.

Mycelium ranks among the largest living organisms on the planet [1]. It features a porous structure made up of tubular filaments known as hyphae. Depending on the species and growth conditions, hyphae typically have diameters between 1 and 30 microns and can extend from just a few microns to several meters in length [2]. Fungi comprise approximately 144,000 recognized species within the kingdom Fungi, encompassing yeasts, rusts, smuts, mildews, moulds, and mushrooms. Additionally, several fungus-like organisms, such as slime moulds and oomycetes (commonly referred to as water moulds), are often misclassified as fungi despite belonging to the kingdom Chromista. Fungi are among the most ubiquitous organisms on Earth, playing critical roles in both environmental and medical contexts. While many species are free-living in soil or aquatic environments, others engage in parasitic or symbiotic interactions with plants and animals. Fungal growth occurs through the extension of filamentous structures known as hyphae, which collectively form the mycelium, the main vegetative body of the organism. Organic matter is enzymatically degraded externally, with the resulting nutrients subsequently absorbed into the mycelium [3].

Insulation made with fungal mycelium represents a novel and innovative type of natural insulation. Mycelium, a complex root structure of fungi, has emerged as a versatile and sustainable source for producing natural building materials. Mycelium composites, which consist of a complex system of hyphae (filaments) combined with natural substrates, yield highly porous and environmentally friendly materials. These composites not only offer an ecological alternative to conventional petroleum-based insulation materials but also provide numerous advantages, including cost-effective, eco-friendly production methods and a minimal environmental footprint.

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The suitability of mycelium also lies in its potential to contribute to a circular economy. Mycelium is increasingly being applied in various industries today, serving as a packaging material, an alternative to plastic fillers or in the design industry for decorations and furniture. The production of bio-composites requires minimal energy and can utilize agricultural waste, further enhancing sustainability.

This study focuses on the development of fully natural, biodegradable thermal insulation, which can be recycled and reintegrated into the soil at the end of its life cycle. Given the growing emphasis on sustainable materials, research on mycelium-based insulations has yielded promising results. The present work involved initial sample testing, with particular attention given to the material's structural integrity, binding potential, binding duration, and the overall mycelium growth process.

It is hypothesized that the final samples will exhibit a structure comparable to that of synthetic thermal insulations, such as polystyrene, leading to similar thermal conductivity properties. The outer layer of the sample is expected to provide protective casing for the internal thermal insulation core. Given the promising thermal properties of the stem pith and the smooth structure of mycelium, the combination of these materials, with mycelium as a natural binder, is anticipated to yield an effective bio-composite insulation.

2 METHODOLOGY

Materials

Sunflower stems (Fig. 1) used for the preparation of composite samples were collected from local fields in Galanta, Slovakia, in August 2024, following the harvest of the flower heads. The stalks were initially dried outdoors under ambient conditions, then cut into smaller sections and further dried at room temperature. The raw sunflower pith was manually separated from the stems. The sunflower-based plant material was processed using an electric rotary cutter equipped with a bladed mechanism suitable for coarse mechanical shredding of biomass. The input material (stalks, pith, mix) was manually fed into the hopper and fragmented by rotating steel blades. A heterogeneous substrate was obtained with particle sizes ranging approximately from 0.5 to 20 mm, predominantly within the 3–10 mm range. The resulting mixture contained both fibrous and granular components and was subsequently used as the base substrate for mycelium inoculation (Fig. 2). Moreover, materials collected earlier in September 2020 from Dvorianky, Slovakia, were used for sample preparation. These materials included sunflower heads left as residual biomass after mechanical harvesting, as well as a plant mixture remaining after the harvesting and crushing process. These materials were not refined by additional grinding.

Fig. 1 Sunflower field after harvesting.

Fig. 2 Grounded sunflower stems.

As a binder, a mycelium growth process was selected, enabling the connection of the natural base material with a natural, biologically-derived binder. The mycelium used in this study was sourced from the civic association Drž Hubu, based in Bratislava, Slovakia.

Mycelium composites preparation

The mycelium cultivation process involved several key stages. Initially, replicated vegetative mycelium tissue was inoculated into a substrate composed of natural materials with favourable thermal properties. The substrate was

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supplemented with essential nutrients, including calcium and carbohydrates, as well as water in order to promote growth. This mixture was placed into filter patch bags, where the inoculation phase was allowed to proceed, enabling the mycelium to permeate the entire mixture.

Following complete colonization, after 16 days, the mycelium-overgrown structure was disrupted to homogenize growth and ensure uniform density across the composite. The homogenized mixture was then transferred into plastic moulds to support further structural development. The blocks were cultivated for an additional 10 days under proprietary environmental conditions, which included controlled adjustments to temperature, humidity, oxygen, and carbon dioxide levels to facilitate adequate surface tissue formation. After the formation of a dense mycelium surface layer, the samples underwent a drying process in a hot air oven at 50°C for 4 hours. This step effectively inactivated the fungal cells, halting further mycelium growth and stabilizing the composite material.

Four basic samples were prepared (Fig. 3), each derived from a different part of the sunflower plant. Sample 1 was obtained from the top (head) portion of the plant, Sample 2 was made from the mixture of plant residues left on the field after harvest, Sample 3 was sourced from the inner portion of the stem, and Sample 4 was derived from the outer stem.

The samples were prepared by standardizing the volume of the natural component, accounting for the proportion of inoculated grain with mycelium, as well as the water and nutrient content. Particular care needs to be given to the mixing process, as it can significantly influence the total volume of the mixture due to the potential compaction of the natural material.

Fig. 3 Initial inoculation of samples.

Properties tests

The measurements were conducted under laboratory conditions, with the samples stabilized at a temperature of 23.7 °C and a relative humidity of 53%. The bulk density of the samples was determined in accordance with STN EN 1602 – Thermal insulating products for building applications – Determination of density. Each sample's dimensions (length, width, and thickness) were measured using a caliper with an accuracy of ± 1 mm five times and the average values were determined. The samples were then weighed using a digital scale with a precision of ± 0.1 g and also five measurements were averaged.

Thermal conductivity values of the samples were measured using the Isomet 2114, a handheld instrument designed for direct measurement of heat transfer properties. Thermal conductivity was measured on four fabricated samples. Each sample underwent five individual measurements, and the final thermal conductivity value for each was calculated as the average of these five measurements.

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3 RESULTS

Sample manufacturing

This section presents the results of the manufacturing process for the mycelium-based bio-composite samples, which were developed to assess their potential as a sustainable thermal insulation material. The samples were created through the inoculation of mycelium into a nutrient-rich agricultural waste substrate, followed by controlled growth, moulding, and drying processes.

Fig. 4 Growth Process of Sample 1(Heads); 4a- Mixture after mycelium growth, prior to moulding; 4b- One day after moulding - beginning of growth process; 4c- Sample after drying process.

The first sample was manufactured from sunflower head part Fig.4. The initial mycelium colonization displayed on Fig. 4a progressed more slowly compared to other samples. However, once the material was moulded, a uniform and dense surface layer of mycelium successfully developed. The structure along the edges was firm and well-grown, forming a closed and cohesive surface Fig. 4c. Upon sectioning, the internal structure was slightly brittle, with visible gaps between larger particles that were not fully colonized by the mycelium. Nevertheless, distinct mycelial filaments bridged these gaps, indicating partial integration.

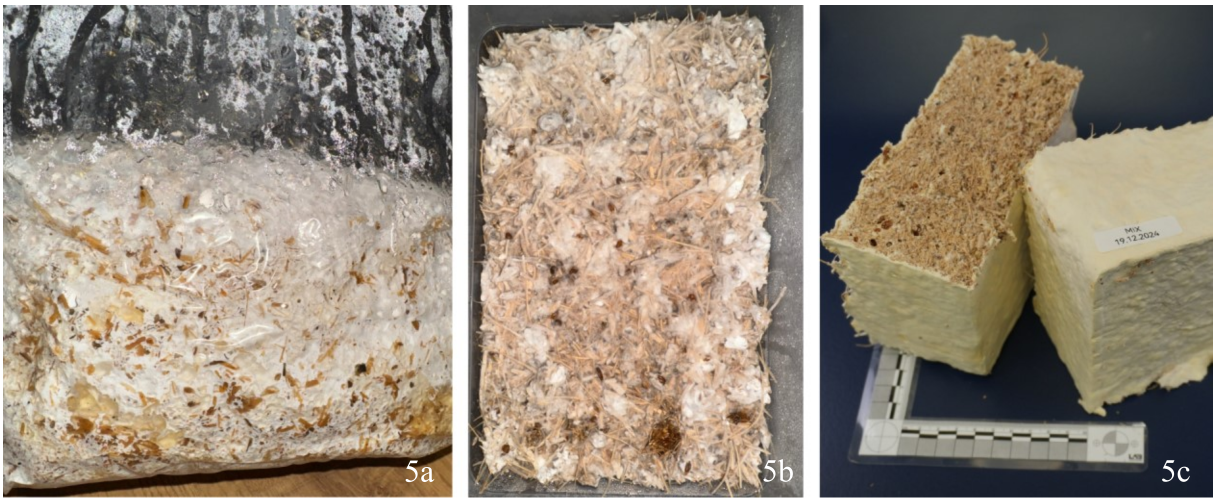

Fig. 5 Growth Process of Sample 2 (Mix); 5a- Mixture after mycelium growth, prior to moulding; 5b- One day after moulding - beginning of growth process; 5c- Sample after drying process.

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Second sample Fig.5 was manufactured from the agricultural waste left on fields after harvesting, a grinded mixture of the stem from harvester. The sample showed on a Fig.5c displayed a slightly less crumbly structure upon cutting compared to the stem-based samples. The plant fibres were visibly coated with a web-like layer of mycelium. The surface exhibited a smooth, delicate texture with a well-formed, uniform layer.

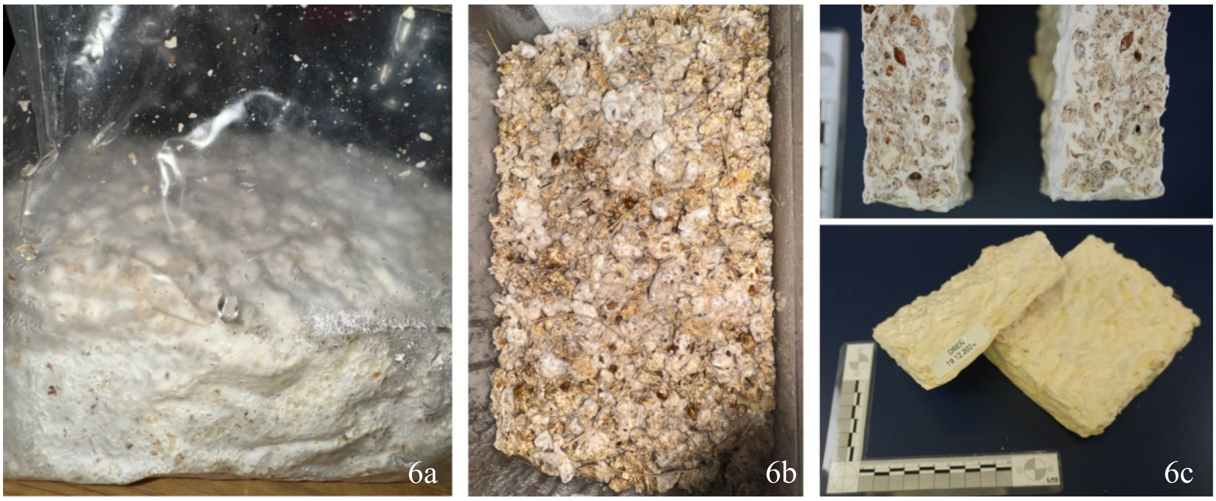

Fig. 6 Growth Process of Sample 3 (Pith); 6a- Mixture after mycelium growth, prior to moulding; 6b- One day after moulding - beginning of growth process; 6c- Sample after drying process.

Sample 3 was manufactured from the soft part of the sunflower stem, the pith – Fig.6. The sample mixture containing pith exhibited the fastest mycelium colonization compared to all other samples, resulting in a significant difference during the sample breakdown and transfer into the mould. The surface structure showed on Fig. 6b after colonization was notably uneven, primarily due to the presence of large fragments formed during substrate breaking and moulding. However, the gaps between particles were beautifully filled with mycelium, resulting in a solid, non-brittle structure. The final sample's structure on Fig. 6c closely resembled a synthetic polystyrene insulation, with the mycelium effectively filling the large gaps created during the crushing of the colonized mixture before moulding.

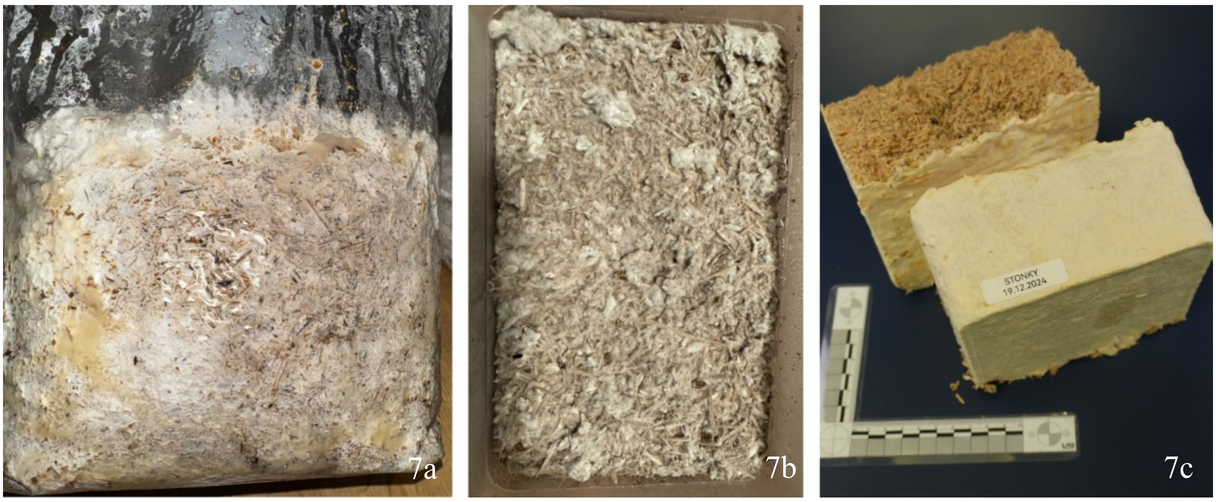

Fig. 7 Growth Process of Sample 4 (Stem); 7a- Mixture after mycelium growth, prior to moulding; 7b- One day after moulding - beginning of growth process; 7c- Sample after drying process.

The fourth sample was manufactured from the outer part of the stem – bark. The process is shown in Fig. 7. The colonization rate (Fig. 7a) was similar to samples 1 and 2. The sample derived from plant stems exhibited

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a brittle internal structure, with reinforcement primarily along the surface – Fig. 7c. Upon sectioning, the core disintegrated easily. The stem fibres were visibly colonized by a web-like network of mycelium, while the outer layer formed a delicate, smooth skin.

Properties of samples

All four samples were measured for thermal conductivity and density. The results are shown in Tab.1.

Tab. 1 Measured properties of bio-composite samples.

Sample number	Material	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Density ($kg \cdot m^{-3}$)
Sample 1	Sunflower heads composite	0.0573	155.83
Sample 2	Sunflower mix composite	0.0564	126.93
Sample 3	Sunflower pith composite	0.0621	184.80
Sample 4	Sunflower stem composite	0.0494	155.22

4 DISCUSSION

The hypothesis of this experiment was that the initial test batch of samples would be entirely based on natural materials and exhibit excellent thermal insulation properties, competitive with those available on the market. The use of mycelium was expected to function as a natural binder, offering inherent thermal insulation properties while also providing structural reinforcement to the thermal insulation core composed of natural materials.

During the preparation of the inoculated mixture, we encountered challenges related to the volume of the natural material during sample mixing. All samples had the same volume of natural base. All samples, except for the stem mixture, were mechanically mixed, which resulted in the compaction of the mixture and a reduction in volume. The stem mixture was manually mixed, preserving its fluffy structure and larger volume. Interestingly, it was observed that the stem mixture was the most brittle of all the samples. The pith-based mixture experienced the greatest volume loss due to its very fine structure; however, it ultimately formed the strongest bond, being the most thoroughly colonized by mycelium.

After inoculation and transfer of the samples into filter bags, mycelial growth was observed. The growth rate was noticeably slower in the sample derived from the plant heads, while it progressed significantly faster in the sample from the plant pith. It is hypothesized that this variation in growth rate was influenced by the nutritional content in the different plant parts.

It was observed that after final drying and sectioning, the samples were not compact but exhibited a loose internal structure. The only sample with substantial colonization was the one containing the stem pith. Complete internal colonization of all samples had been anticipated. The exact cause of this outcome remains unclear; however, it is hypothesized that a longer incubation period in the mould might have allowed for better internal colonization. Nutritional factors and external environmental conditions may also have contributed to this result. Further experimental testing will be necessary to clarify these factors.

The measured thermal properties did not align with initial expectations. The anticipated thermal conductivity was approximately 0,03 $W \cdot m^{-1} \cdot K^{-1}$, based on the favourable thermal performance of sunflower pith, which is typically around 0,033 $W \cdot m^{-1} \cdot K^{-1}$ [4]. However, the test results indicated higher values according to Tab. 1. Furthermore, mycelium-based composites utilizing agricultural waste substrates have been reported to exhibit thermal conductivity values ranging from 0,05 to 0,07 $W \cdot m^{-1} \cdot K^{-1}$) [5].

The bio-composite samples produced from different parts of the sunflower plant exhibited bulk densities ranging from 126.93 to 184.80 $kg \cdot m^{-3}$, and thermal conductivity values between 0.0494 and 0.0621 $W \cdot m^{-1} \cdot K^{-1}$. These values partly fall within the range commonly reported for natural insulation materials showed on Tab.2 (e.g., hemp, straw, sheep wool), which typically show thermal conductivities of 0.038–0.0587 $W \cdot m^{-1} \cdot K^{-1}$, depending on composition and density.

Tab. 2 Comparative overview of thermal conductivity and density of selected commercial insulation materials.

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Product type	Material	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Density ($kg \cdot m^{-3}$)	Reference
Natural material	Hemp shives	0.0587	108.36	[6]
Natural material	Straw bale	0.0520	80	[7]
Natural material	Sheep wool	0.038-0.054	10-25	[8]
Natural material	Sunflower pith	0.033-0.050	36-152	[4], [8]
Composite	Hemp shives, sapropel	0.059-0.073	210-410	[9]
Composite	Sunflower pith, pectin	0.034	38.8	[10]
Product	Steico flex 036, wood fibre	0.036	60	[11]
Product	PIR insulation, Kingspan	0.022	30	[12]
Product	EPS Isover Greywall	0.031	14.5-18	[13]

Sunflower pith naturally possesses an alveolar structure, which provides advantageous hygric and thermal properties [14]. This has been demonstrated in studies on bio composites, where a sunflower stem sample with a pectin binder achieved a thermal conductivity of 0.034 $W \cdot m^{-1} \cdot K^{-1}$ [10]. Compared to conventional synthetic insulation materials such as expanded polystyrene, PIR insulation or natural insulations from wood fibres (ranging 0.033–0.050 $W \cdot m^{-1} \cdot K^{-1}$), the bio-composites demonstrated slightly higher values, but remain within a competitive and relevant range for building insulation.

In terms of density, the mycelium-based composites exhibit higher values compared to conventional commercial insulation materials, indicating limited comparability in this parameter. Notably, the sample with the highest density (Sample 3 – pith composite, 184.80 $kg \cdot m^{-3}$) also exhibited the highest thermal conductivity (0.0621 $W \cdot m^{-1} \cdot K^{-1}$), supporting the widely observed trend that increased density often leads to increased thermal conductivity, likely due to reduced porosity and a greater proportion of solid phase that conducts heat more efficiently. The relatively high thermal conductivity measured for Sample 3 is likely due to the significant presence of mycelium in the composite, which may have disrupted the porous structure of the sunflower pith during both the mixing and growth processes. As shown in Fig. 6, no distinct remnants of the sunflower stem are observable, suggesting that the material was fully decomposed and processed by the mycelium.

In contrast, Sample 4 (stem composite) showed the lowest thermal conductivity (0.0494 $W \cdot m^{-1} \cdot K^{-1}$) despite having a similar density (155.22 $kg \cdot m^{-3}$) to Sample 1, suggesting that its less compacted, airier structure preserved by manual mixing enhanced its insulating performance by retaining more air pockets.

5 CONCLUSION

Fungi are critical components of Earth's ecosystems and hold significant potential for biotechnological applications due to their unique growth and metabolic processes. They grow by extending hyphal filaments that form the mycelium, which externally digests and absorbs organic matter. Despite their adaptive capacity, successful colonization in structured substrates depends on multiple factors, including incubation time, nutrient availability, and environmental conditions.

In this study, the outcomes highlighted challenges in achieving uniform fungal colonization across samples. Although the stem pith sample exhibited complete and compact mycelial growth, other samples remained internally loose and only partially colonized. These results deviated from expectations, indicating potential limitations in experimental design or environmental parameters. One possible explanation is the insufficient incubation period, which may have restricted mycelial development inside the substrates. Nutritional constraints and external conditions, such as humidity and temperature fluctuations, may have further influenced fungal colonization.

These findings underscore the complexity of optimizing fungal growth in structured systems. Understanding the interplay between incubation time, substrate properties, and environmental factors is essential for improving fungal colonization strategies. Future research should focus on testing longer incubation durations, optimizing substrate composition, and fine-tuning environmental parameters to enhance growth outcomes. Such advancements will not only deepen our understanding of fungal biology but also pave the way for more effective applications in fields such as biomaterials, environmental remediation, and sustainable architecture.

Although the thermal conductivity of the developed mycelium-based composite is higher than that of commercial products, the material offers ecological advantages and sufficient insulation potential for low-energy applications.

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