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Review Article

Alternative applications of mushroom mycelium for environmental sustainability: opportunities, challenges and future perspective

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ABSTRACT

In recent years, there has been a growing interest in finding sustainable alternatives to traditional packaging materials such as thermocol/polystyrene. One promising solution that has gained attention in recent past is the use of fungal mycelium, the fast-growing vegetative part of fungi, as a substitute for polystyrene. Fungal mycelium, a substance derived from diverse biological and agricultural wastes, is regarded as a secure, non-reactive, sustainable, organic and environmentally friendly packaging material. The substance exhibits the ability to form self-assembling bonds, resulting in the rapid production of robust and environmentally degradable materials. The objective of this study is to conduct a comprehensive examination of the developments and present status of mycelium-based technology, with a particular emphasis on its utilization in the fields of packaging and insulation; and how mycelium can be used to remediate agro-industrial wastes. By examining the advantages, challenges, and potential drawbacks of using mycelium as a substitute for polystyrene, this paper aims to shed light on the feasibility and sustainability of mycelium-based materials.

Keywords: Mycelium, packaging, bio-composite, polystyrene, fungi, mycelium-based materials

Mycelium is a material derived from fungal sources (Islam *et al.*, 2017), which is used in many applications ranging from packaging, tissue engineering, regenerative medicine, meat alternatives, etc. (Bitting *et al.*, 2022; Vandelook *et al.*, 2021). Mycelium is composed of glucans, chitin, chitosan and glycoproteins, with chitin being the second most abundant polysaccharide on earth (Vandelook *et al.*, 2021). Mycelial colonies exhibit random interconnections through the process of hyphal fusion, also known as anastomosis, resulting in the formation of a fibre network structure with a random configuration (Fig 1b). The nutritional and environmental conditions exert significant control over the branching density and network topology. The hyphal wall is composed of proteins, beta-glucans, and chitin, as depicted in Figure 1(c) (Islam *et al.*, 2017). Its filamentous network structure has mechanical properties that are determined by network density, filament elasticity and branching. Furthermore, mycelium can be used to create foam-like materials with resilient properties, and also for sustainable materials such as Mycoflex™ and Reishi™. In terms of packaging applications, mycelium can be combined with $CaCl_2$ to create antimicrobial properties. Deacetylation of chitosan can be used to liberate amino groups for cross linking of mycelium (Vandelook *et al.*, 2021). When subjected to tension and compression, mycelium shows an initial linear-elastic regime followed by a plateau regime with a softened response, with an elastic modulus ranging from 600 to 2000 kPa. Its ultimate strength in tension varies from 100-300 kPa, depending on material density, and it also displays strain-dependent hysteresis

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and stress softening effects (Islam *et al.*, 2017). These properties make mycelium an attractive alternative to conventional synthetic packaging materials, such as polystyrene foam, and it could also be used in smaller commercial products and larger architectural prototypes (Bitting *et al.*, 2022).

A. Mycelial Growth

Mycelium, which is a rapid-growing vegetative component of a fungus, is comprised of microscopic white fibres forming self-assembling bonds quickly (Dweck, 2006). Mycelium is capable of storing reserve substances and fats that lead to a rise in weight without the formation of new cells or the consumption of nitrogen (Calam, 1969). In contrast, fungi and actinomycetes develop much slower, with their threads extending and changing in composition as they age. Yeasts and bacteria, however, tend to reproduce at a much faster rate in comparison (Calam, 1969). Mycelium foam exhibits notable suitability for the growth of members belonging to the order Polyporales, including *Ganoderma* sp.. The accumulation of carbon dioxide (CO2) within the substrate medium resulting from cellular respiration establishes a gradient that facilitates the outward growth of mycelium towards a more favourable environment. Although there is a lack of comprehensive reports regarding the growth modeling of this fermentation strategy, the primary factor responsible for the expansion of the mycelium is the carbon dioxide (CO2) gradient generated by cellular respiration. In addition, it has been observed that certain growth conditions, including temperature, levels of gaseous CO2, and relative humidity, have the potential to promote the extensive proliferation of aerial hyphae. These conditions are considered to be optimal for inhibiting the differentiation of the mycelium into fruiting bodies. The growth pattern of hyphae is distinguished by an expansion that occurs in an outward direction, moving away from the substrate and into the surrounding air. It is possible to attain a substantial amount of mycelial biomass on solid feedstocks (Vandelook *et al*., 2021).

B. Advantages of Mycelium Material

Mycelium-based materials have a range of advantages over other materials, ranging from their environmental credentials to their low-cost manufacturing (Elsacker *et al.*, 2021). Sustainable alternatives are widely regarded as having the potential to enhance the environmental performance of various applications (Elsacker *et al*., 2021, Bitting *et al.*, 2022). Mycelium-derived materials possess complete compostability, as certain packaging materials can undergo biodegradation within a span of approximately 40 days. Consequently, these materials present an appealing choice for implementing circularity. The mycelium-based materials have a less shelf life due to their quick degradation over time and low energy consumption during production (Bitting *et al.*, 2022). In relation to mechanical characteristics, these materials have demonstrated strength levels that are comparable to those of polystyrene foams and particle boards (Elsacker *et al.*, 2021). However, their mechanical properties are relatively low, necessitating their utilization in combination with structurally informed geometry and suitable digital fabrication techniques (Bitting *et al.*, 2022). Mycelium-based materials also have customizable properties based on their composition and manufacturing process, and can be used as thermal and acoustic insulation foams. They have the potential to serve as substitutes for foams, timber, and plastics in a range of construction applications. Additionally, they offer the opportunity to repurpose plentiful agricultural by-products and waste materials into more sustainable alternatives (Fig 3) having fire safety properties, high acoustic absorption, high insulation properties and low thermal conductivity that outperform traditional construction materials (Jones *et al.*, 2020, Bitting *et al*., 2022, Alemu *et al.*, 2022). The mycelium based products have the potential to be 3D printed in order to overcome the limitations of mold-grown mycelium composites (Elsacker *et al.*, 2021). These properties of mycelium-based materials give a distinctive advantage over alternative materials in the realm of research and design applications within the field of architecture (Bitting *et al*., 2022).

C. Mechanical properties of mycelium-based materials

Mycelium is a type of fungus that has recently been gaining attention for its potential applications. With its foam-like properties and low-density nature, mycelium can be used to produce a variety of materials for a wide range of applications. Mycelium materials can be produced through two main methods, pure mycelium materials (PMM) and mycelium-bound composites (MBC). PMM involves the growth of mycelium on organic waste and binding it to form a composite material, while MBC involves the growth of mycelium around lignocellulosic substrates (Bitting *et al.*, 2022). MBC possess favourable characteristics, including their lightweight nature and ability to undergo biodegradation. These attributes render them highly suitable for a wide range of applications, encompassing acoustic insulation, thermal insulation, packaging, fire retardants, structural building components, etc.. The properties of MBC enable them to meet specific application requirements. The substrate mixture type, specifically the combination of particle-based (sawdust) and fibrous (straw) materials, was studied as one of the parameters. The study focused on the mechanical property of compressive strength in MBC (Ghazvinian and Gürsoy, 2022). The investigation of the mechanical behaviour of MBC was conducted through an integrated approach that combined experimental and computational methods. The authors employed a numerical homogenization technique to develop a three-dimensional finite element model, aiming to enhance the understanding of the composite behaviour (Islam *et al*., 2018). The density of the substrate has been found to have an impact on the mechanical behaviour of MBC, as stated by previous research. The mechanical strength of a material is directly influenced by the density of the substrate (Ghazvinian and Gürsoy, 2022). They reported that there exists an inverse correlation between the duration of MBC cultivation and the mechanical properties of the material. In the absence of the hyphal binder, the substrate functions as an irregular aggregation of particles and exhibits minimal mechanical efficacy (Ghazvinian and Gürsoy, 2022). The composites exhibited a soft elastic response at small strains, followed by stress softening and hysteresis under cyclic compression. At larger strains, the composites demonstrated marked stiffening due to the densification of stiff particles. Mycelium density and particle size had an effect on the mechanical properties of the composites (Islam *et al*., 2018). The properties of MBC enable them to meet specific application requirements. The dead load of MBC material was considered to be insignificant, and higher grades of MBC could be employed for applications that endure minimal loads due to the inherent strength of the materials. Mechanical tests served as the primary factors in the optimization of the structural configurations of MBC, as stated by previous researchers. Ghazvinian and Gürsoy, (2022) developed computational form-finding methods for the purpose of designing and fabricating compressive structures using MBC. The utilization of materials with enhanced mechanical properties facilitates the creation and construction of structural forms that can withstand compressive forces. The study also investigated many aspects of cultivation period, encompassing both whole and partial cultivation, using bags and formworks. The study examined the impact of different cultivation parameters on compressive strength and revealed that MBC manufactured utilizing low-weight substrate combinations demonstrate similar compressive strength to that of polystyrene foams. They also observed that MBC demonstrates comparatively reduced compressive strength in comparison to polyurethane and phenolic formaldehyde resins. The selection of appropriate temperatures for hot-pressing substrates necessitates careful consideration in order to prevent the occurrence of material weakness or thermal degradation. The application of heat-pressing induces a transformation in the properties of MBC, transitioning them from a foam-like state to a wood-like state (Ghazvinian and Gürsoy, 2022).

D. Applications of Mycelium based materials

Mycelium-based materials (MBm) can be used for various applications, such as noise absorption, fire resistance, construction material, structural support, gap filling materials, packaging, and even digital fabrication techniques. These materials can be used at various scales, from small commercial products to larger architectural applications. One of the primary obstacles encountered in the process of expanding the utilization of mycelium-based materials pertains to the insufficient comprehension of the hierarchical arrangement within the mycelium network. Additionally, successful implementation necessitates effective collaboration among microbiologists, material scientists, manufacturers, and designers (Yang *et al.*, 2021). Nevertheless, significant progress in fermentation techniques has expanded the potential for functional applications of mycelium materials. Mycelium-based materials possess biodegradable properties, rendering them well-suited for consumer markets as an environmentally-friendly product. Mycelium-derived materials possess the capacity to be employed in digital fabrication methodologies and exhibit promising characteristics that render them comparable to plastics, thereby suggesting their potential as a versatile material (Bitting *et al.*, 2022, Vandelook *et al.*, 2021).

Mycelium-based composites refer to materials that are derived from fungal mycelium. These materials have found applications in various industries, including construction, furniture, and interior design (Bonenberg *et al.*, 2023). Promising results was obtained by adding different additives to the base substrate such as coffee silver skin, beech wood and perlite rock in order see the influence of the additives on the physical properties of the MBCs (Dehn and Kotan, 2021). New insulation materials were developed using mycelium of *Miscanthus giganteus* (Dias *et al.*, 2021). According to Bonenberg *et al*. (2023), the mycelium based composites exhibit porous and uneven surfaces but their thermal conductivities were found to be similar to those of commercially available ecological insulation materials. Additional comprehensive investigations are required in order to enhance the fundamental characteristics of mycelium materials and guarantee consistent outcomes with predominantly uniform attributes (Dehn and Kotan, 2021). In addition, research has been conducted to measure the human acceptance of these materials, with the results being mostly positive or not-negative. Nevertheless, the provenance of MBC materials from natural sources and concerns regarding fungal growth presents obstacles to their widespread adoption. Comparative analyses conducted with wall cladding samples demonstrated a general preference for ceramic reference materials over MBCs in terms of overall evaluation and their ability to harmonize with contemporary interior aesthetics (Bonenberg *et al.*, 2023) (Fig 4).

(i) Mycelium for packaging and insulation

Utilization of mycelium-based materials has gained significant interest in recent times, primarily owing to their capacity to potentially bring about a transformative impact on the construction sector. Mycelium is a biomaterial derived from fungal sources that can be used for insulation, packaging, and other applications (Bitting *et al.*, 2022, Soh *et al.*, 2020, Dweck, 2006). The cost of manufacturing mycelium-based insulation is low, making it competitive with standard materials. Mycelium insulation panels outperform market-leading but unsustainable materials in terms of thermal conductivity (Bitting *et al.*, 2022). The incorporation of agricultural waste and bamboo microfibres, along with chitosan and mycelium, facilitates the development of a composite blend that possesses the properties of workability, extrudability, and buildability. The process of extrusion, which has not yet been extensively studied in the context of mycelium-bound composites, offers the advantages of low energy consumption, design flexibility, and desirable structural characteristics (Soh *et al.*, 2020). According to Jones *et al*. (2020), mycelium composites possess several advantageous characteristics, including cost-effectiveness, ease of production, and environmental sustainability. Mycelium composites have customizable material properties based on their composition and manufacturing process. They are suitable for specific applications such as insulation, paneling, and furnishings. These materials have the potential to serve as sustainable substitutes for energy-intensive synthetic materials in the fields of packaging and insulation (Jones *et al*., 2020, Dweck, 2006). The use of mycelium for packaging and insulation can help reduce the reliance on non-biodegradable materials like polystyrene. The utilization of mycelium composites has demonstrated potential as effective materials for thermal and acoustic insulation foams (Jones *et al*., 2020). However, they have poor mechanical properties that limit their use. The compression modulus of mycelium composites is around 0.1 to 0.4 MPa after drying. Strategies are needed to increase the mechanical properties of mycelium-bound composites for wider applications in packaging and insulation (Sivaprasad *et al*., 2021). The main challenges for using mycelium-bound composites in the construction industry are low mechanical properties, high water absorption, and the lack of standard production and testing methods. Further researches and developments are needed to address these challenges and improve the applications of mycelium-bound composites in the construction industry (Bitting *et al.*, 2022).

(ii) Remedy to agro-industrial wastes

Mycelium can be used to produce lightweight, strong and inexpensive bio-composites, which can be used to replace petroleum-based plastics. A range of lignocellulosic agricultural residues, including sawdust, wheat bran, rice husk, and cotton hulls, have the potential to be utilized in the production of bio-composites with significant value. This can be achieved through the application of fungal mycelium as a natural binding agent (Dweck, 2006). Hence, it is necessary to assess the toxicity and genotoxicity of mushrooms if they are used for bioremediation purposes. The genotoxicity of mushrooms used for mycoremediation is highly influenced by the presence of genotoxicants in the waste used for their cultivation. Although there are some disadvantages associated with mycoremediation, such as the time required for adaptation and clean-up, its advantages include the low-cost, small space requirement, and less skilled personnel needed for application in the field (Kulshreshtha *et al.*, 2014). Mycoremediation of waste from the environment by mushroom also eliminates the need for transporting toxic materials to treatment sites and can be used to remediate non-sterilized polychlorinated dibenzo-p-dioxins/dibenzofurans (PCDD/F) contaminated soil (Cheng *et al.*, 2023). Mycelium can also be cultivated on agricultural wastes such as spent green tea and coffee grounds residue, and the mycelium-free liquids (MFLs) obtained from the cultivation can be used to treat contaminated soil. The removal mechanism of PCDD/F contaminants using MFLs is biased towards oxidation rather than dehalogenative reduction. The addition of borate-fructose complex as a mediator can further enhance the removal efficiency of PCDD/F contaminants by 17%, and the removal efficiencies of PCDD/F contaminants using MFLs were found to be comparable to those of a regular medium (Cheng *et al.*, 2023). MBm require minimum energy for production and can be self-growing, and the characteristics of mycelium-based materials can be modified by changing their nutrient substrates (Antunes *et al.*, 2020). For example, it has been observed that elevating the hot-pressing temperature enhances the thermal decomposition resistance of the composites. Additionally, the growth of mycelium has been found to disrupt the structure of the cotton stalk particles and degrade constituents such as hemicelluloses and lignin. The utilization of mycelium for the remediation of agro-industrial wastes involves the cultivation of cotton stalks with the white rot fungus *Ganoderma lucidum* within a block mould and hot pressing of composite of mycelium and cotton stalks at temperature of 200°C, leads to the formation of densely packed structures and the establishment of novel chemical bonds resulting in comparable flexural and internal bonding strength to non-load bearing fibreboard (Dweck, 2006).

(iii) Mycelium based materials in construction material, plastics and engineered wood

Mycelium-derived materials have been employed in a diverse array of applications, encompassing both low-value uses like packaging and gap-filling, as well as high-value applications involving composite materials for structural purposes (Yang *et al.*, 2021). The incorporation of mycelium-based materials in combination with diverse substances, such as wood, has been documented (Bitting *et al.*, 2022). These materials have the capability to fulfill distinct purposes, including providing structural stability, offering protection against fire, and enhancing acoustic insulation. Furthermore, the utilization of mycelium-based materials has been observed in the context of noise absorption (Yang *et al.*, 2021). There exist two main approaches in the development of engineered materials using mycelium: pure mycelium materials (PMM) and mycelium-bound composites. Both methodologies yield materials with low density and foam-like characteristics as a result of the presence of air within the mycelial network and mycelia matrix. The process of PMM entails the production of a mycological biopolymer through the cultivation and extraction of a liquid culture consisting solely of mycelium (Bitting *et al.*, 2022). According to the Bitting *et al.* (2022), MBC has the ability to develop a thickened epidermis and facilitate the fusion of distinct blocks when it remains viable. The potential of PMM lies in its ability to effectively laminate lignocellulosic materials together. The integration of various mycelium-based material typologies has the potential to generate novel bio-composites that exhibit enhanced thermal, acoustic, and mechanical characteristics. Mycelium-derived materials have been utilized in the fabrication of materials that exhibit comparable elastic modulus and density to naturally occurring substances such as cork and wood (Appels *et al*., 2019). They have been explored for larger architectural applications and digital fabrication techniques (Bitting et al., 2022). These bio-composites can be used to create foam and sandwich composites for construction structures. Mycelium can be used to create larger low-density objects like synthetic foams and plastics, as well as synthetic planar materials such as plastic films and sheets. The ability to customize the material properties of MBC through the modification of fungal species, growth circumstances, and post-growth processing processes facilitates their capacity to meet specific mechanical requirements. Mycelium-derived materials also have the potential to be utilized in the production of semi-structural components such as paneling, flooring, furniture, and decking. The mycelium network undergoes growth and generates fibres that facilitate the binding of these individual components, resulting in the formation of a material characterized by porosity (Yang *et al.*, 2021). A Myco Board is an engineered product that might easily displace wood and other items made of engineered wood. The usage of recognized carcinogens like urea-formaldehyde in many manufactured wood products has clearly been replaced by a method in which particles are joined together by naturally occurring mycelium rather than resins. This might perform better than particle and medium density fiberboards (Fig 5).

(iv) Mycelium as a substitute for Polystyrene

Mycelium can be used as an effective alternative to polystyrene in various applications. It has comparable strength to polystyrene foams and boards (Dweck, 2006), making it a viable replacement for single-use applications that have a lower carbon footprint (Vandelook *et al*., 2021). Numerous studies have demonstrated that augmenting the porosity of the substrate can enhance the diffusion of oxygen and facilitate the formation of a compact mycelium network. Consequently, this phenomenon can result in a notable enhancement in the mechanical characteristics of composites bound by mycelium. Additionally, Reishi™, a mycelium-based material, can be used as an alternative to polystyrene in the production of leather alternatives (Sivaprasad *et al.*, 2021). However, current research has focused mainly on agricultural substrates, a limited number of fungi, and post-processing options for mycelium composites, as well as their influences. In order to comprehend the potential of mycelium composites as substitutes for polystyrene, it is imperative to conduct an investigation and comparative analysis of their properties. Furthermore, strategies that increase the mechanical properties of mycelium-bound composites must be developed in order to expand their range of application (Dweck, 2006). Finally, mycelium composites have a shorter carbon turnover time and are biodegradable, making them a more sustainable alternative to polystyrene (Vandelook *et al.*, 2021).

(v) Advantages of using mycelium instead of polystyrene

Mycelium is a biodegradable material that has immense potential for replacing synthetic materials such as polystyrene. In recent years, research into mycelium-based materials has been conducted with the aim of utilizing mycelium to create insulation boards, as well as a range of other products. Mycelium can also be used to create furniture, lighting, and other interior products. Mycelium-based materials (MBs) have properties that can be improved through compression during the growth phases. This makes them a suitable alternative to polystyrene, which is non-biodegradable and has a higher environmental impact (McGaw *et al.*, 2022). Moreover, MBs can be combined with emerging technologies such as 3D printing to optimize structures for specific environmental requirements. Additionally, MBs utilize low cost and abundant agricultural waste, making them biodegradable, while offering wide variations in material properties that depend on growth parameters. Mycelium-based insulation materials have comparable thermal, sound, and fire safety characteristics to polystyrene insulation materials (Fig 7) (Robertson, 2020). In addition, mycelium has been employed as a replacement for the hazardous urea-formaldehyde typically utilized in particle board. Mycelium-based particle boards have been found to possess notable water and fire resistance properties, surpassing the requirements set by building standards. Additionally, these boards have demonstrated the ability to achieve a higher internal bonding strength than what is mandated by building regulations. Mycelium-based packaging is a biodegradable substitute for polystyrene, appealing to customers concerned with plastic waste. Additionally, it is feasible to generate this product on a large scale, whereby the procedure entails creating a three-dimensional virtual representation of the desired shape to be supported, followed by the fabrication of tailor-made thermoform growth trays (McGaw *et al.*, 2022). They observed that mycelium possesses the ability to adapt its growth to the dimensions of the container in which it is cultivated. Furthermore, scientific investigations (Aranda-Calipuy *et al.*, 2023) have indicated that the properties of mycelium exhibit similarities to those of polystyrene. Thus, using mycelium as a biomaterial offers a viable alternative for solid waste management, as it is structurally resistant to bending, lightweight, has low environmental impact (Aranda-Calipuy *et al.*, 2023), and low production cost (McGaw *et al.*, 2022). Additionally, mycelium can be used to align with sustainable development goals and net-zero targets in the construction industry, making it a promising ecological alternative to polystyrene.

(vi) Potential drawbacks of using mycelium instead of polystyrene

Despite its advantages over polystyrene, mycelium-based engineering materials have certain drawbacks. For instance, mycelium's tensile strength is significantly lower than that of polystyrene. Additionally, mycelium has excessive hygroscopicity, which will cause the material to absorb moisture from the environment. This will result in the material's deterioration over time. Furthermore, mycelium is susceptible to biological corrosion, which can be detrimental to its strength and other properties and, finally, mycelium must be deactivated before it can be used as a material. The modification of the SC3 hydrophobin gene can induce alterations in the physical and mechanical characteristics of mycelium. The mechanical characteristics of wild type fungus demonstrate resemblances to those observed in natural substances like as wood, cork, and flax. In order to discover novel fungal species for the purpose of developing mycelium-based materials, the identification of a suitable species or the exploration of previously untapped species may serve to mitigate the aforementioned drawbacks. Regrettably, the existing literature lacks comprehensive guidelines for the discovery of novel species or the analysis of prevalent combinations of fungal species and substrates. Furthermore, there is a dearth of review articles that assess the extent of research conducted on specific fungal species (Sydor *et al.*, 2022).

E. Challenges in developing mycelium applications

The development of MBC offers promising solutions for sustainable and eco-friendly practices. Mycelium materials are biodegradable, renewable, and have a lower carbon footprint compared to traditional petrochemical based materials (Butu *et al.*, 2020). The fabrication methods for mycelium-based materials also contribute to their sustainability, as they often involve utilizing agricultural waste or byproducts (Attias *et al.*, 2021). Moreover, MBC have shown potential in reducing waste and pollution, as they can be composted at the end of their life cycle (Manan *et al.*, 2021). Nevertheless, additional study is required to enhance the efficiency of production methods, enhance the characteristics of materials, and investigate novel applications for materials derived from mycelium (Bitting *et al.*, 2022). With ongoing advancements and efforts in this field, mycelium has the potential to revolutionize various industries by providing sustainable alternatives to conventional materials.

(i) Technical challenges

One of the technical challenges in developing mycelium applications is controlling the growth and morphology of mycelium. The structure of mycelium is characterized by a network of filaments, and its mechanical properties are primarily influenced by the elasticity of these filaments, as well as the degree of branching and density within the network (Islam *et al.*, 2017). Achieving the desired growth patterns and structures can be challenging, as mycelium-based materials require precise control over the substrate and processing methods to achieve specific structures and material functions (Yang *et al.*, 2021). Cultivating mycelium can also be challenging due to its complex cell morphology, ranging from dispersed mycelia to dense pellets (Böl *et al.*, 2020). Therefore, researchers and developers face the task of finding ways to manipulate and control mycelium growth to meet the requirements of various applications.

Another challenge in mycelium application development is ensuring consistent and predictable performance. While mycelium-based materials have shown promise in various fields, including packaging and construction, there is a need for standard methods for production and testing of MBC. The mechanical properties of mycelium materials, such as low strength and high-water absorption can limit their applications (Jones *et al.*, 2020). Additionally, scalability and reproducibility of mycelium fabrication processes are crucial for commercialization (Elsacker *et al.*, 2021).

Overcoming limitations in structural integrity is another significant challenge in mycelium application development. While mycelium has the ability to adopt the shape of a mold, making it an ideal candidate for packaging materials and other structural applications (Manan *et al.*, 2021), there are still challenges in achieving the desired strength and durability. Balancing biodegradability with structural integrity remains a key challenge in utilizing mycelium in the building industry (McGaw *et al.*, 2022). Furthermore, utilization of mycelium-based materials within the building sector has been predominantly confined to small-scale prototypes and architectural installations (Bitting *et al.*, 2022). Addressing these challenges requires further research and innovation to improve the structural properties of mycelium-based materials and ensure their suitability for a wider range of applications.

(ii) Environmental challenges

One of the major challenges in developing mycelium applications is the sourcing and availability of raw materials. Mycelium-based materials require specific types of organic waste or agricultural byproducts as a substrate for growth (Jones *et al.*, 2020). However, the availability and consistent supply of these raw materials can be a challenge, especially on a large scale (Rafiee *et al.*, 2021). The demand for mycelium-based products is increasing, and ensuring a sustainable and reliable source of raw materials is crucial for the development and scalability of these applications (Bitting *et al.*, 2022).

Another significant environmental challenge in mycelium application development is the impact on land and water resources. The cultivation of mycelium requires space and resources, such as water and land, for the growth and maintenance of the fungal networks (Vandelook *et al.*, 2021c). This can put pressure on already limited land and water resources, especially in areas where mycelium production is concentrated. Additionally, the production process may generate wastewater or byproducts that need to be managed properly to prevent environmental pollution (Appels *et al.*, 2019). Mitigating the environmental impact and ensuring sustainable land and water use are essential considerations in the development of mycelium applications.

Managing waste and byproducts generated during the production of mycelium-based materials is another challenge. While mycelium is known for its ability to decompose organic waste, the process of transforming waste into usable products can still generate waste and byproducts that need to be properly handled (Kim, 2022). Finding efficient and sustainable ways to manage these waste streams, such as through recycling or composting, is crucial for minimizing the environmental impact of mycelium application development (Alemu *et al.*, 2022). Additionally, ensuring the safe disposal or reuse of these waste materials is important for maintaining a circular and sustainable production process (Bitting *et al.*, 2022).

(iii) Regulatory and safety challenges

One of the challenges in developing mycelium applications is ensuring compliance with existing regulations and standards. As mycelium-based materials gain popularity in various industries, it becomes crucial to navigate through the regulatory landscape to ensure that these materials meet the necessary requirements. For example, in the building industry, MBC need to demonstrate compliance with building standards through testing and certification (McGaw *et al.*, 2022). Similarly, for mycelium-based composite materials used in applications such as shoe soles, there is a need to develop and test these materials to meet specific safety and performance standards (Siqueira, 2021). Compliance with existing regulations and standards is essential to ensure the safety and quality of mycelium applications (Bitting *et al.*, 2022).

Another challenge in mycelium application development is addressing health and safety concerns. While mycelium-based materials offer numerous benefits such as sustainability and biodegradability, it is crucial to assess any potential health risks associated with their use. Research and testing are required to understand the potential allergenicity or toxicity of mycelium-based materials (Attias *et al.*, 2021). Additionally, the selection of fungal species used in mycelium materials should be based on risk assessment to ensure that they do not pose any health hazards (Van Den Brandhof and Wösten, 2022). By addressing health and safety concerns, the development of mycelium applications can proceed with confidence and ensure the well-being of users and consumers.

Navigating intellectual property and patent issues is another significant challenge in the development of mycelium applications. As the field of mycelium-based materials continues to grow, protecting intellectual property becomes crucial for researchers and industry. However, the unique nature of mycelium materials and the difficulty in patenting living organisms pose challenges in securing intellectual property rights (Hüttner *et al.*, 2020). This can create complexities in terms of commercialization and market competition. Overcoming these challenges requires innovative approaches to intellectual property protection and collaboration among researchers, industry, and legal experts. By effectively tackling these obstacles, the advancement of mycelium applications can thrive, hence contributing to a more sustainable and ecologically conscious future (Bitting *et al.*, 2022).

(iv) Market and commercialization challenges

One of the major challenges in developing mycelium applications is scaling up production and meeting market demand. Mycelium-based materials have gained significant attention across various disciplines. However, the current production capacity is limited, and scaling up the production of mycelium materials is not a straightforward process (Peeters *et al.*, 2023). This is because it requires the development of consistent and reliable supply chains for growing media, as well as the optimization of production methods (McGaw *et al.*, 2022). Meeting the increasing market demand for mycelium-based products will require innovative solutions and investments in research and development (Ecovative, 2022).

Developing mycelium applications at competitive pricing and value proposition is another challenge (Jones *et al.*, 2020). However, the cost of production and processing of mycelium materials is still relatively high compared to traditional materials (Yang *et al.*, 2021). To make mycelium applications commercially viable, it is crucial to develop cost-effective production methods and optimize the manufacturing process (Bitting *et al.*, 2022). Additionally, creating a compelling value proposition that highlights the unique properties and benefits of mycelium-based materials will be essential for market acceptance and adoption (Alemu *et al.*, 2022).

(v) Awareness challenges

Educating and creating awareness among consumers and industries is another significant challenge in the development of mycelium applications. Despite the potential benefits of mycelium-based materials, there is still a lack of awareness and understanding among consumers and industries about their properties, applications, and sustainability advantages (McGaw *et al.*, 2022). Educating consumers about the environmental impact of traditional materials and showcasing the potential of mycelium-based alternatives can help to drive demand and market acceptance (Siqueira, 2021). Additionally, collaborating with industries and engaging in knowledge-sharing initiatives can help to overcome barriers and foster the adoption of mycelium applications (Vandelook *et al.*, 2021). By raising awareness and promoting the benefits of mycelium-based materials, the market potential for these innovative products can be further realized ("InsightAce analytic", 2020).

F. Cost of mycelium-based materials

Mycelium-based materials represent a novel category of bio-composites that exhibit both sustainability and affordability (Javadian *et al.*, 2020). Notably, the production cost of these materials is significantly lower, approximately 80 times less, when compared to blocks made from cement and gypsum. Additionally, they can be made with locally available raw materials making them cost-effective (Alemu *et al.*, 2022). Nevertheless, the challenges associated with mycelium-bound composites include inadequate mechanical properties, elevated water absorption, and the absence of established production and testing protocols (Javadian *et al.*, 2020). Consequently, a considerable amount of research has been devoted to examining techniques for the manufacture and treatment of mycelium-based composite materials as well as evaluating and contrasting the characteristics of various mycelium composites and post-production alternatives (Dweck, 2006). The current research on mycelium composites has mostly focused on a limited number of fungal species and lignocellulosic waste combinations. This indicates the necessity for additional exploration of alternative sources of lignocellulosic waste in order to potentially mitigate expenses. Moreover, the present research emphasis predominantly revolves around agricultural substrates and a restricted range of fungus, hence necessitating the expansion of investigations to ascertain additional economically viable alternatives. The investigation of mycelium composites as viable alternatives to fossil-based polymers, such as expanded polystyrene (EPS), indicates the possibility of cost reduction (Dweck, 2006). However, their low mechanical properties have limited their applications as load-bearing structural elements. In order to mitigate the expenses associated with mycelium-based materials, it is imperative to establish a strong connection between structurally informed geometry and suitable digital fabrication techniques, while also recognizing the potential of their low embodied carbon to greatly enhance the environmental sustainability of buildings (Bitting *et al.*, 2022). Therefore, further research and development efforts are needed to reduce the cost of mycelium-based materials.

G. Techniques to improve mycelium-based materials

The performance of mycelium-based materials can be improved in a variety of ways, such as by utilizing certain fungal species and optimizing fermentation conditions. This can be done by using efficient fermentation setups, which can reduce the growth phase of mycelium materials to 5-14 days, and by combining biodegradable elements with non-biodegradable elements. Furthermore, the properties of mycelium materials can be improved by incorporating various polymeric or fibre additives and chemically modifying the cell wall components. Additionally, the growth of mycelium can be controlled at both the microscopic and macroscopic level. In addition, the food and biotechnological industry has already successfully implemented large-scale fermentation of filamentous fungi. This has been achieved through the utilization of both submerged bioreactor and solid-state fermentation techniques, each possessing distinct attributes (Vandelook *et al.*, 2021). However, 3D-printing may not be suitable for improving the performance of mycelium-based materials, whereas Odico's diamond-threaded abrasive wire rotation on electrically propelled flywheels can increase production speed and enable cutting of solid materials. Additionally, CNC milling can be ineffective in improving the performance of mycelium-based materials, and hot-wire cutting is limited to thermally cut materials. Furthermore, the maximum thickness of mycelium-based products is ~150 mm, and producing large monolithic mycelium blocks is almost impossible due to the lack of fungal growth in the core of the material (Vandelook *et al.*, 2021). Reishi™, a mycelium-based leather alternative, can improve the performance of these materials, and Mycoflex™ foam-like material can provide resilient properties (Elsacker *et al.*, 2021). The fabrication process of mycelium composites has also been found to have self-healing properties, and a robotically manufactured system can enhance the growth of large-scale mycelium composites. Jiang et al. (2016) investigated a manufacturing system that utilizes a core of mycelium-composite foam sandwiched between two laminate layers of fabric or mycelium mat, and 3D printing has been studied as a process to improve the performance of mycelium-based materials by allowing fungi to grow inside the printed samples. The growth performance of *Trametes versicolor* was found to be generally favourable, exhibiting a high rate of mycelial growth. Additionally, it was observed that the introduction of additional nutrients to beech sawdust (SD) and spent mushroom substrate (SMS) can enhance the performance of materials based on mycelium. Nevertheless, it was observed that *Ganoderma lucidum* exhibited a comparatively slower rate of mycelial growth on substrates based on Saw Dust. Conversely, *T. versicolor* demonstrated the ability to efficiently recycle SMS and *G. lucidum* SD-based substrates, resulting in the production of lightweight materials characterized by a low thermal conductivity (Vandelook *et al.*, 2021). All in all, these processes are expected to further improve the performance of mycelium materials and stimulate their breakthrough.

CONCLUSION

This paper aims to interpret the main findings and implications of the research, as well as to identify any limitations and suggest future research directions on the alternative uses of mycelium based composites. Firstly, the mechanical properties of mycelium, including its filamentous network structure, elasticity, and branching, have been found to make it an attractive alternative to polystyrene foam. Mycelium can be used to create foam-like materials with resilient properties, which are suitable for packaging applications. Furthermore, materials derived from mycelium demonstrate a notable reduction in thermal conductivity, a significant increase in acoustic absorption, and enhanced fire safety characteristics, surpassing those of conventional construction materials. The aforementioned characteristics render mycelium-derived materials highly appropriate for a diverse array of applications, encompassing but not limited to noise attenuation, fire retardancy, structural reinforcement, and gap-filling materials. However, it is important to note that mycelium-based materials have limitations. One limitation is their reduced shelf life due to quick degradation over time. This may restrict their use in certain applications where durability is crucial. In addition, the mechanical properties of materials derived from mycelium are currently insufficient for use in load-bearing structural components. Consequently, the incorporation of structurally informed geometry and suitable digital fabrication techniques becomes necessary. Moreover, it is important to note that the growth rate of mycelium can exhibit variability based on the specific fungal species employed, which can potentially have implications for the overall production procedure. Notwithstanding these constraints, the study underscores the viability of utilizing mycelium-derived materials in the context of sustainable packaging endeavours. The biodegradable nature of mycelium-based materials, coupled with their ability to be composted within approximately 40 days, aligns with the principles of circularity and environmental sustainability. Moreover, the low cost of manufacturing mycelium-based insulation materials makes them competitive with standard materials, further enhancing their appeal. Future research directions in this field may involve exploring ways to improve the mechanical properties of mycelium-based materials without compromising their sustainability. This could involve incorporating polymeric or fiber additives, as well as exploring chemical alterations of cell wall components. Additionally, further investigation is needed to optimize the growth conditions and fermentation techniques for mycelium production, as well as develop models for predicting and controlling mycelium growth. In conclusion, the research paper provides a comprehensive review of the sustainable packaging applications of mycelium-based materials.

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