

Mushroom Based Sustainable Biopolymer Composites

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ABSTRACT

Synthetic polymers remain intact in nature for many years after the expire and cannot be included in the natural recycling material in anywhere. Fossil resource-based polymer manufacture is endangering current supplies and has a daily detrimental impact on the circular economy. The harmful consequences of polymers on the environment, biopolymers a class of polymers created by living organisms like plants, animals, and microalgae might be a great substitute. Because of biopolymers that are recyclable, low-emission, or environmentally friendly, a wide range of new subjects are emerging in this field. There are several industries where composite materials based on these biopolymers which function as natural adhesives find use, including the packaging, textile, furniture, and industrial design sectors, as well as architectural and structural insulation design. This composite can replace traditional building materials, which are expensive, nonbiodegradable, and have significant emissions. It also exhibits exceptional mechanical strength, hydrophobic qualities, and thermal stability. The kind of substrate and strain, the length of incubation, and the method of manufacturing are some of the variables influencing the composite's physicochemical properties.

Keywords: Biopolymers, Sustainable composite materials, Circular economy, Natural adhesives, Eco-friendly building materials.

INTRODUCTION

Mycelium-based composites (MBCs) are a new class of bioengineered materials made by fusing fungal mycelium with lignocellulosic byproducts. These materials' sustainability, biodegradability, low embodied energy, and recyclability have attracted a lot of research interest (Appels et al., 2019; Elsacker et al., 2020; Jones et al., 2020). MBCs perform exceptionally well ecologically, despite the fact that their mechanical qualities may not yet be on par with plastics or synthetic woods (Islam et al., 2022). Mycelium is made up of hyphal networks with chitin, β -glucans, proteins, and lipids in their cell walls; these biochemical structures are directly influenced by the makeup of the substrate and the sources of nutrients (Haneef et al., 2017; Appels et al., 2019). Lignocellulosic feedstocks typically consist of cellulose, hemicellulose, and lignin, providing fermentable sugars and aromatic compounds required for fungal metabolism (Yang et al., 2021; Jiang et al., 2022).



Figure 1 : Hyphal–Lignocellulosic Interaction Mechanism in the Formation of Mycelium-Based Composites

In order to create cohesive composites, fungi release cellulolytic and ligninolytic enzymes that break down plant cell walls and integrate the substrate into three-dimensional mycelial matrices (Attias et al., 2020; Ghazvinian et al., 2021). Growth termination is accomplished by stabilising the material through heat treatment or drying (Elsacker et al., 2020). MBCs offer more customisation and design freedom and require less processing than synthetic composites (Khan et al., 2023).

MBCs provide significant environmental advantages, including high recyclability, cheap production energy, waste valorisation, and the lack of hazardous binders (Jones et al., 2020; Manan et al., 2022). Although MBCs have lesser mechanical strength than concrete or metals, they are superior in terms of fire resistance, acoustic attenuation, and aesthetics (Jiang et al., 2022; Li et al., 2023).

Table 1: Overview of Mycelium-Based Composite Systems

Material (Substrate / Fungus)	Source	Type of MBC	Major Usage	Key Reference (Year)
Agricultural residues (straw, corn stalks, husks) + <i>Pleurotus ostreatus</i>	Crop waste from farms	Structural biocomposite panels	Insulation boards; building envelopes	Jones et al. (2020); Jiang et al. (2022)
Sawdust + <i>Ganoderma lucidum</i>	Wood industry by-products	Rigid molded composites	Interior panels; acoustic materials	Ghazvinian et al. (2021); Khan et al. (2023)
Hemp hurds + fungal mycelium	Industrial hemp processing waste	Lightweight insulating composite	Thermal and sound insulation	Ahmed et al. (2024)
Mixed lignocellulosic fibers + filamentous fungi	Agro-industrial waste streams	Molded packaging forms	Protective packaging (alternative to EPS/PUR foams)	Jones et al. (2020); Park et al. (2024)
Fine mycelium (pure mycelial mats)	Controlled fungal fermentation	Mycelium leather	Leather alternatives in fashion and upholstery	Attias et al. (2020); Appels et al. (2023)
Engineered mycelial sheets (e.g., MycoTex-type materials)	Laboratory-grown fungal biomass	Textile fiber composites	Sustainable garments and wearable materials	Singh et al. (2024); Zhao et al. (2025)
Material (Substrate / Fungus)	Source	Type of MBC	Major Usage	Key Reference (Year)
Hybrid fiber blends + mycelium matrix	Agricultural and forestry residues	Furniture-grade bio-composites	Furniture and decorative interiors	Appels et al. (2023); Park et al. (2024)

Applications include furniture, interior materials, automotive parts, architecture, packaging, leather substitutes, and textile replacements (Ghazvinian et al., 2021; Appels et al., 2023; Singh et al., 2024). As sustainable substitutes for hazardous and animal-based materials, pure mycelium-derived biomaterials like myco-leather are being produced (Attias et al., 2020; Park et al., 2024). Functional composites for bioelectronics, sensing, and self-repairing structures are the subject of emerging research (Adamatzky et al., 2023; Zhao et al., 2025).

One important physical characteristic that is affected by pressing, fungus species, and substrate type is density (Manan et al., 2022; Li et al., 2023). Dimensional stability is impacted by shrinkage caused by dehydration (Yang et al., 2021). According to thermal conductivity studies, MBCs have a lower embodied energy than conventional insulation materials as glass wool and polystyrene (Jiang et al., 2022; Ahmed et al., 2024).

Process

Selection of Fungal Species

One of the most important factors influencing the structural and functional performance of mycelium-based composites is the choice of fungal species. The hyphal diameter, branching pattern, enzymatic activity, and growth kinetics of various fungi vary, and these differences have a direct impact on material integrity and colonisation efficiency (Appels et al., 2019; Elsacker et al., 2020). Rapid radial growth rates lower the possibility of contamination during large-scale production and allow consistent substrate binding.

Because of their potent ligninolytic enzyme systems, which can break down lignin, cellulose, and hemicellulose all at once, white-rot fungi are most frequently utilised. According to Ghazvinian et al. (2021) and Singh et al. (2024), species like *Pleurotus ostreatus*, *Trametes multicolour*, and *Ganoderma lucidum* generate dense interwoven mycelial networks that function as natural biological binders, improving cohesion between substrate particles. Laccases and peroxidases, two extracellular enzymes produced by these fungi, alter lignocellulosic fibres and strengthen interfacial bonds.

Research shows that fungal species have a substantial impact on the final morphology, porosity, stiffness, and compressive strength of composites even when the same substrates and environmental conditions are utilised (Park et al., 2024; Zhao et al., 2025). While some species produce lightweight porous structures appropriate for insulation applications, others develop thicker hyphae that result in materials with higher densities. As a result, the choice of species must be in line with the composite's intended engineering use.

Selection of Substrate

In the creation of MBC, the substrate serves as both a source of nutrients and a framework for structural reinforcement. Because of their lignocellulosic composition and sustainability benefits, agricultural and agroindustrial wastes like straw, sawdust, rice husk, wood chips, corn stover and coconut coir are frequently used (Jones et al., 2020; Manan et al., 2022). These materials compose the bulk matrix of the composite and supply the carbon sources required for fungal metabolism.

Mechanical performance is significantly influenced by the size of the substrate particles, their chemical makeup, and their ability to retain moisture. While coarse particles enhance aeration but may decrease mechanical strength, fine particles increase surface contact area and density (Li et al., 2023). During mycelial colonisation, the cellulose-to-lignin ratio controls the pace of breakdown and binding effectiveness.

By altering pore structure and lowering flammability, functional additives such rice husk ash and biochar improve fire resistance, thermal stability, and dimensional integrity (Ahmed et al., 2024; Singh et al., 2024). Furthermore, localised feedstock selection is critical for scalable and sustainable industrial production since regional substrate availability significantly lowers transportation costs and carbon footprints (Islam et al., 2022).

Substrate Sterilization

The purpose of sterilisation is to get rid of competing microorganisms that could prevent fungal growth or lower the quality of the composite. In addition to competing for nutrition, contaminants like bacteria and mould can create compounds that erode mycelial connections. Thus, quick and consistent colonisation is guaranteed by efficient sterilisation (Appels et al., 2019; Elsacker et al., 2020).

Pasteurisation at moderate temperatures, autoclaving under high pressure steam, and chemical sterilisation with hydrogen peroxide or mildly acidic solutions are common methods of sterilisation (Manan et al., 2022). While pasteurisation is a more affordable option for large-scale applications, autoclaving delivers the maximum sterility but consumes more energy.

Mechanical characteristics like density and compressive strength are more reproducible across production batches when sterilisation procedures are followed consistently (Singh et al., 2024). After sterilisation, proper moisture adjustment is also crucial since too much moisture or too little moisture can postpone fungal colonisation.

Inoculation Process

Fungal cultures that are actively growing are introduced into the prepared substrate through inoculation. Grain spawn inoculation and liquid culture inoculation are the two main inoculation techniques that are frequently used (Islam et al., 2022). While liquid cultures allow fungal biomass to be evenly distributed throughout the substrate, grain spawn offers solid nutrient transporters that encourage quick colonisation.

During the early phases of growth, supplementing with carbs like glucose or starch increases metabolic activity and speeds up hyphal expansion. A sufficient concentration of inoculum guarantees quicker colonisation, reducing the risk of contamination and enhancing structural homogeneity. Because uniform mycelial growth facilitates improved particle binding and load distribution, the inoculation method has a substantial impact on mechanical properties such as compressive strength, elasticity, and Young's modulus (Ahmed et al., 2024; Li et al., 2023). For consistent material performance, inoculation parameter optimisation is therefore crucial.

Molding and Packing

Mycelium composites' final structural behaviour, density gradients, and shape are all determined by moulding. Because they are durable and simple to demold, moulds made of PVC, polyethylene, silicone, or thermoformed polymers are frequently used (Elsacker et al., 2020; Ghazvinian et al., 2021).

A key factor in mechanical performance is packing density. While dense packing yields stronger structural composites, loose packing yields lighter materials with greater porosity that are appropriate for thermal or acoustic insulation. Additionally, packing direction affects hyphal connection and fibre alignment, which in turn affects anisotropic mechanical behaviour (Khan et al., 2023).

Fungal development requires oxygen availability, hence proper aeration during moulding is essential. In order to promote consistent colonisation throughout the structure, ventilation apertures are frequently incorporated into mould design.

Incubation and Colonization

Fungal mycelium spreads throughout the substrate during incubation, bringing particles together to form a cohesive composite. Depending on fungal species, substrate composition, moisture content, and climatic factors including temperature and humidity, colonisation times normally vary from 5 to 42 days (Yang et al., 2021; Ahmed et al., 2024).

Before developing a thick outer skin layer that improves surface strength and resistance to mechanical harm, mycelial development first takes place inside. Uniform growth is encouraged and uneven density formation is prevented by controlled environmental conditions.

Long-term incubation improves bonding density and strength, but it can also cause excessive substrate degradation (Manan et al., 2022; Singh et al., 2024). In order to balance mechanical performance and structural stability, the incubation period must be optimised.

Drying and Densification

By eliminating any remaining moisture, drying is used to stop fungal metabolic activity and stabilise the composite structure. Oven drying, convection heating, freeze drying, and hot pressing are common drying techniques (Islam et al., 2022; Ahmed et al., 2024).

By simultaneously drying and compressing the material, hot pressing improves hyphal bonding and particle compaction, greatly increasing mechanical strength. Higher pressure increases load-bearing capability and decreases porosity.

Dimensional stability, density, and shrinkage are all significantly impacted by drying time and temperature. While regulated drying results in homogeneous constructions with increased durability, rapid drying may lead to cracking (Li et al., 2023). For industrial scalability, drying parameter optimisation is crucial.

Surface Finishing

Surface finishing improves mycelium composites' visual appeal and functional performance. Protective coatings are used to increase longevity because untreated materials are typically porous and moisture-sensitive.

While wax coats like beeswax and carnauba wax form protective barriers against moisture absorption, natural oils like linseed oil and coconut oil penetrate the surface and increase hydrophobicity (Attias et al., 2020; Park et al., 2024). Surface smoothness and mechanical resistance are further enhanced by bio-resin coatings.

Current research investigates hybrid surface treatments and bio-based coating systems that improve barrier qualities against microbial and water vapour degradation without sacrificing biodegradability (Zhao et al., 2025). Thus, surface engineering increases the possible uses of MBCs in interior design, building, and packaging.

Quantification of Material Properties for Performance Comparison

Mycelium-based composites must be quantitatively evaluated in order to determine how competitive they are with traditional insulation materials like glass wool, mineral wool, and polymeric foams. According to Appels et al. (2019), reproducibility and trustworthy cross-study comparison are made possible by standardised measurement of physical and thermal parameters. In a similar vein, Elsacker et al. (2020) emphasised that industrial acceptability of bio-based insulation materials requires performance benchmarking.

Density

One of the main factors affecting mechanical strength and thermal insulation effectiveness is density. The density of MBCs typically varies between 40 and 350 kg m⁻³, depending on the fungal species, substrate particle size, and packing conditions (Jones et al., 2020; Manan et al., 2022). Densities of lightweight insulation-grade materials typically range from 60 to 150 kg m⁻³.

Densification and hot pressing can raise density by 20–60%, improving structural integrity, according to experimental studies by Li et al. (2023). These density values overlap with those of glass wool and mineral wool insulation goods, according to comparative research published by Ghazvinian et al. (2021).

Thermal Conductivity

Energy efficiency and insulation performance are determined by thermal conductivity. According to measurements compiled by Appels et al. (2019), depending on porosity and moisture content, MBC thermal conductivity normally falls between 0.029 and 0.065 W m⁻¹ K⁻¹. Yang et al. (2021) found lower conductivity values in highly porous composites, confirming similar ranges.

Optimised mycelium composites can attain insulation performance comparable to glass wool (0.030–0.045 W m⁻¹ K⁻¹) and mineral wool (0.035–0.050 W m⁻¹ K⁻¹), indicating their viability as sustainable thermal insulation options, according to Singh et al. (2024).

Compressive Strength

Applications involving handling and construction require mechanical stability. According to research by Elsacker et al. (2020), compressive strengths varied from 0.05 to 1.20 MPa, depending on the type of fungus and the makeup of the substrate. According to Ahmed et al. (2024), additional gains were seen when hot pressing was used, with strengths nearing 2.0 MPa.

In comparison to low-density fibre insulating materials, denser mycelial networks improve stress distribution and raise Young's modulus, improving material durability, according to research by Park et al. (2024).

Thermal Stability and Fire Performance

According to thermogravimetric investigations published by Singh et al. (2024), MBCs start to degrade thermally at about 200–300 °C, with significant breakdown taking place between 300 and 400 °C. According to Ahmed et

al. (2024), adding mineral additives like ash or biochar enhances char formation and lowers flammability by 15–35%.

Water Absorption and Moisture Behaviour

According to Li et al. (2023), untreated MBCs show water absorption values between 150 and 400% by weight because of their porous architecture. According to Attias et al. (2020), surface modification techniques greatly decrease moisture uptake, reducing absorption to 40–120% and enhancing dimensional stability.

Acoustic Insulation Performance

Acoustic testing conducted by Ghazvinian et al. (2021) showed sound absorption coefficients ranging from 0.60 to 0.95 within frequencies of 500–4000 Hz, comparable to mineral wool insulation. These findings support the application of MBCs in acoustic panels and interior building materials.

Applications of Mycelium-Based Composites

Composites made of mycelium have become a versatile bio-material with uses in packaging, industrial design, building, and sustainable textiles. They are promising substitutes for petroleum-based materials due to their lightweight construction, biodegradability, low energy production requirements, and adjustable mechanical qualities. Their place in environmentally conscious production systems and circular economy models is highlighted by recent studies.

Building and Construction

Because of their multifunctional performance qualities, the building industry is one of the most potential application areas for mycelium-based composites. MBCs are appropriate for insulating panels, partition walls, ceiling tiles, and non-load-bearing architectural elements because of their low thermal conductivity, fire retardancy, sound absorption, and biological resistance.

Mycelium composites offer efficient thermal insulation that is on par with traditional fibre materials while having a smaller environmental impact, according to studies by Jiang et al. (2022) and Ahmed et al. (2024).

When MBCs burn, they emit much less smoke and harmful gases than conventional materials like expanded polystyrene and particle board. Jones et al.

(2020) and Singh et al. (2024) claim that this lower emission profile enhances interior and building envelope fire safety performance. Furthermore, the chitin-rich fungal cell walls support the organism's natural defence against termites and microbial deterioration.

Current architectural research investigates the incorporation of MBCs into modular housing, bio-based construction systems, and regenerative design methodologies.

While Khan et al. (2023) stressed their compatibility with circular construction systems where materials can be recycled or composted after service life, Ghazvinian et al. (2021) emphasised that fungal growth permits self-binding structures requiring little synthetic adhesives. These characteristics encourage less wasteful building and sustainable urban development.

Product and Industrial Design

Designers may produce intricate designs without using energy-intensive machining techniques because to mycelium's moldability and biological fabrication process. According to Attias et al. (2020), mycelium development takes place inside moulds, allowing for near-net-shape production and reducing material waste.

According to innovations reported by Appels et al. (2023), designers are using MBCs more frequently for consumer goods such lampshades, acoustic panels, footwear parts, and biodegradable electronics casings. In

sustainable product design, the material's texture, organic look, and adjustable density offer distinctive tactile and aesthetic aspects.

Furthermore, Singh et al. (2024) noted that tuning growth conditions allows modification of stiffness, porosity, and surface finish, enabling applications ranging from rigid structural products to flexible cushioning materials. Industrial designers increasingly incorporate mycelium composites into eco-design frameworks emphasizing lifecycle sustainability and reduced carbon footprint.

Household Furnishings

Mycelium composites are becoming more popular in home furniture and interior design because of its natural aesthetic appeal, lightweight construction, and acoustic performance. Chairs, tables, shelving units, and ornamental wall pieces made from moulded mycelium composites are among the demonstrations described by Appels et al. (2023).

In comparison to synthetic foams and wood composites bound with formaldehyde resins, MBC-based furniture components offer greater sustainability and sufficient mechanical stability for interior applications, according to research by Park et al. (2024). By absorbing sound reflections, the porous microstructure improves indoor acoustic comfort.

Mycelium's versatility is further demonstrated via decorative installations and lighting fixtures. Its translucent textures and organic shapes are used by designers to create eco-friendly interior goods that adhere to biophilic design principles and green construction concepts.

Sustainable Packaging

The most sophisticated commercial use of mycelium-based materials at the moment is packaging. Mycelium packaging is a biodegradable substitute for protective cushioning made of expanded polystyrene (EPS) and polyurethane (PUR) foams.

Because of its cellular structure and interconnected hyphal networks, MBC packaging exhibits exceptional shock absorption, according to Jones et al. (2020).

Mycelium packaging offers adequate compressive strength and vibration dampening for moving delicate items like electronics and glassware, according to research by Ahmed et al. (2024). These materials are completely compostable and, given the right circumstances, break down naturally in a matter of weeks, in contrast to petroleum-based foams.

According to Park et al. (2024), commercial platforms like MycoComposite and MycoFlex use mold-grown fabrication techniques to create personalised package shapes without the need for extra machining. This strategy promotes scalable production in line with the ideas of the circular economy while lowering manufacturing waste.

Leather and Textile Alternatives

Fungal mycelium can be processed into flexible sheet-like materials that mimic the texture and durability of leather while remaining biodegradable, according to Attias et al. (2020).

Innovations like MycoTex and Fine Mycelium, described by Appels et al. (2023), demonstrate customisable thickness, texture, and surface finishes suitable for footwear, fashion accessories, and upholstery; these materials significantly reduce the environmental impacts associated with livestock farming and petrochemical-based synthetic leather.

Research summarized by Singh et al. (2024) indicates that mycelium textiles require substantially lower water and energy inputs during production compared with conventional textile fibers.

Emerging developments reported by Zhao et al. (2025) focus on bio-coated mycelium fabrics that improve durability, flexibility, and resistance to moisture while maintaining biodegradability. Consequently, mycelium-

based textiles are gaining traction in sustainable fashion and wearable technologies as industries transition toward renewable biomaterials.

Table 2: Applications of Mycelium-Based Composites

Application Area	Key Features / Properties	Representative Uses	Key References (Year)
Building and Construction	Low thermal conductivity; fire retardancy; acoustic damping; termite resistance; reduced smoke and carbon emissions during combustion	Building envelopes; insulation panels; sustainable architectural components; circular design integration	Jiang et al. (2022); Ahmed et al. (2024); Jones et al. (2020); Singh et al. (2024); Ghazvinian et al. (2021); Khan et al. (2023)
Product and Industrial Design	High moldability; tunable mechanical properties; natural aesthetics; lightweight structure	Eco-designed consumer goods; structural art pieces; commercial design products	Attias et al. (2020); Appels et al. (2023); Singh et al. (2024)
Household Furnishings	Aesthetic adaptability; structural stability; environmentally friendly composition	Furniture; lighting fixtures; decorative interior elements	Appels et al. (2023); Park et al. (2024)
Sustainable Packaging	Compostability; biodegradability; shock absorption; renewable raw materials; moldable forms	Protective packaging; cushioning materials; alternatives to EPS and PUR foams; commercial systems such as MycoComposite and MycoFlex	Jones et al. (2020); Ahmed et al. (2024); Park et al. (2024)
Leather and Textile Alternatives	Biodegradable; lower environmental impact; customizable textures; flexible structure	Fungal leather substitutes (e.g., MycoTex, Fine Mycelium); sustainable textile fibers; fashion and wearable materials	Attias et al. (2020); Appels et al. (2023); Singh et al. (2024); Zhao et al. (2025)

CONCLUSION

In Recent research, mycelium-based composites are becoming more widely acknowledged as practical substitutes for wood-based and petroleum-derived materials, especially in the context of low-carbon construction and the circular bioeconomy. Research regularly shows that fungal species with strong lignocellulosic degrading capabilities and the ability to create dense, interwoven hyphal networks greatly improve mechanical integrity and interfacial bonding. Although variability is still a problem, optimised composites show competitive compressive strength, enhanced thermal insulation, and advantageous acoustic damping. Substrate composition (cellulose–hemicellulose–lignin ratio), fungal strain selection, incubation conditions, and post-processing methods like hot pressing or heat inactivation all have a significant impact on material performance.

In order to get over mechanical constraints and moisture sensitivity, recent developments concentrate on densification techniques, bio-based hydrophobic coatings, mineral reinforcement, and hybrid fibre integration. Standardisation procedures, life-cycle assessment validation, growth process automation, and large-scale modular manufacturing are where MBCs are headed. To assure repeatable performance evaluation, standardisation actually entails using globally accepted testing frameworks, such as ISO 8301 for thermal conductivity, ISO 844 for compressive strength, and ISO 29767 for water absorption. Under identical testing settings, these techniques allow MBCs to be directly compared to traditional insulation materials such as glass wool and mineral wool. By establishing consistent testing conditions and acceptance standards, standardised characterisation also aids in industrial quality control, building certification, and regulatory approval. Therefore, in order to move mycelium composites from laboratory-scale innovation to commercially recognised building

materials, evaluation mechanisms based on ISO and ASTM must be implemented. Commercialisation will be accelerated by integration with sustainable product design frameworks and green building certifications. As long as microbiologists, material scientists, and engineers continue to work together across disciplines, MBCs have the potential to become a common sustainable material platform in the building and product industries of the future.

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