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REVIEW

Mycelium-based biocomposites: synthesis and applications

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Abstract

In order to create eco-friendly composite materials for industries like construction and furniture, it is necessary to find substitutes for commonly used materials that harm the environment. One potential solution is to explore biopolymer alternatives to synthetic polymers. Recently, mycelium-derived products have been examined as a viable solution for large-scale production. Mycelium, which comes from fungi, particularly mushrooms, binds organic waste together and acts as an adhesive, forming a degradable substance that can take almost any shape. The material properties are influenced by factors such as the type of fungus used, the waste used as food, growth kinetics, and post-synthesis processing. These factors enable the creation of materials with desired properties such as elasticity, porosity, texture, patterns, colour, conductivity, high-temperature performance, corrosion resistance, and cost-effectiveness. These materials are widely used in building, bio-textiles, sound insulation panels, leather, and furniture. This article provides an introduction to mycelium-based materials, their synthesis, material-based design strategies, and industrial applications.

Keywords Mycelium-based materials · Biocomposites · Compression moulding · Recycling

Introduction

Indiscriminate plastic usage has harmed the environment, leading researchers to explore sustainable alternatives. One promising area is the production of biopolymers from renewable resources, specifically from the agriculture and timber industries' lignocellulosic waste. Due to higher operating costs and a lack of effective disposal methods, lignocellulosic waste is typically burned or processed as domestic waste in the majority of the world's countries (Sun et al. 2016; Shafer 2020; Kaur and Singh 2022). Mycelium, a thread-like structure found in fungi, can grow on lignocellulosic waste materials to produce bio-agglomerates, which are solid matrices. Mycelium-based biomaterials have been around since the 1980s, and they offer an environmentally friendly solution to reusing and recycling biological waste (Alemu et al. 2022). Yamanaka and Kikuchi (1991) first reported the mycelium's capacity to bond, yielding paper and some construction materials. These materials can be composted at the end of their useful life without harming the environment (Meng et al. 2017). Mycelium-based composites can also be designed to have a wide range of properties, such as stiffness, elasticity, and water resistance, making them suitable for various applications (Myers and Antonelli 2018).

Fungal mycelium is a polymeric composite material made up of natural polymers such as mannoproteins, hydrophobins, chitin, glucans, and other protein polymers (Holt et al. 2012; Jones et al. 2017; Girometta et al. 2019).Fungi create mycelium-derived materials by growing their intertwined threadlike hyphae network into a substrate.Mycelium is a natural adhesive that holds the components together (Manan et al. 2021). Mycelium-based materials are made when fungi grow on organic waste materials, combining decomposition products into a physical composite (Butu et al. 2020). These materials can be designed to have any desired feature, e.g. hard, stiff, soft, porous, elastic, flexible, weightless, or extremely dense. They can also be mechanically and thermally stable, corrosion- and water-resistant, and mimic foam, wood, leather, plastic, or paper (Amobonye et al. 2023; Balaeş et al. 2023; Majib et al. 2023). They are also inexpensive, fast-growing, and possess antibacterial and antioxidant qualities, making them ideal for architecture, design, cosmetics, and fashion.

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Mycelium-derived material design

The last decade saw the emergence of the "Growing Design" concept, where living organisms synthesise new materials (Mironov et al. 2009; Ciuffi 2013; Rath et al. 2014; Rognoli et al. 2015; Montalti 2021). Different designers and researchers have explored the use of mycelium to develop innovative, sustainable, and versatile industrial materials with unique properties, ranging from leather-like to papery textures, showing promise in both technological and aesthetic aspects (Montalti 2021; McGaw et al. 2022; Sydor et al. 2022). The materials produced by this design technique are bio-based substitutes for traditional materials. Material Driven Design (MDD) is a more contemporary idea that emphasises and bridges the material's distinctive experiential and technical features suitably and creatively (Karana et al. 2015; Majumdar et al. 2017). Finding new product applications can be aided by this strategy, which supports material design during development. Fungi have gained attention as viable sources of biomaterials due to their potential in various industries (Cerimi et al. 2019; Almpani-Lekka et al. 2022; Mohseni et al. 2023). Mycelium is unique because it can overgrow and take on a variety of shapes. Materials from mycelium can be employed as pure mycelial materials (PMM) or as mycelium-bound composites (MBC)(Holt et al. 2012; Haneef et al. 2017).

Mycelial leather

Leather is known for its robustness and adaptability, but some people hesitate to wear animal-made products due to moral implications and concerns about long-term viability. Vegan/mycelia leather has become popular in the fashion industry due to its fine quality, appearance, texture, and durability. It is also biodegradable, making it a better option for synthetic leather. The fashion industry is exploring alternatives to natural leather, which requires a lot of processing time and years of cattle farming to produce as a by-product of the meat industry (Waltz 2022). Livestock farming has serious sustainability challenges and is responsible for significant greenhouse gas emissions (Reisinger and Clark 2018). Furthermore, post-processing of animal hides requires toxic chemicals and energy-intensive processing, resulting in sludge waste, making leather an environmentally unsustainable product (Richey et al. 2015). All these problems make leather a more environmentally unsustainable product.

Mycelial leather/ PMM is a biopolymer created by harvesting a liquid culture of pure mycelium (Jones et al. 2017). PMM does not contain any lignocellulosic substrates and is characterised solely by the biological properties of the fungal species, source of nutrients, and growing conditions. The notable feature of these materials is their reliance on liquid mycelium cultures (Karana et al. 2018). Mycelial growth does not require light and converts waste into a valuable product (Udayanga and Devmini Miriyagalla 2021). Harvesting a fungal liquid culture yields pure mycelium. When in a static environment, filamentous fungi on a liquid surface develop a hyphal mat that, when dried, produces materials with various characteristics that mimic leather, linen, or rubber (Elsacker et al. 2023). The material's colour, translucency, and stiffness can change depending on the additives/plasticizers, such as glycerol, sorbitol, PEG, glycol, or ethanol, added to the mycelium during the last phase of its development (Haneef et al. 2017; Raman et al. 2022; Amobonye et al. 2023). The mat-like structure formed during growth becomes a leathery product when further treated with mild acids (tannic acid, genipin, vanillin; procyanidin), alcohols, and dyes, followed by compression, drying, and embossing (Cerimi et al. 2019; Antinori et al. 2021; Kaiser et al. 2023). Raman et al. (2022) have derived thermally stable mycelium leather using *Fomitella fraxinea* mushroom. The most significant impact on mycelial leather is visible following cross-linker and coating treatment, reducing its Young's modulus and ultimate tensile strength to 8.49 MPa. Plasticized methods render the mycelium's surface hydrophobic and prevent surface leaching. They concluded that it is feasible to modify the tensile strength by adjusting mycelial development and leather processing by adding plasticizers, cross-linkers, and hot pressing (Raman et al. 2022).

The processing of mycelium leather is quite simple and does not require fancy equipment or a skill set for mass production. The finished product has a strength, look, and feel similar to leather from an animal.The entire process, from spore germination to finished product, only takes a few weeks, compared to the years needed to raise an animal to adulthood (Gougouli and Koutsoumanis 2013). The degree of colonization, the fungal skin's thickness, and the filamentous composite components' uniformity all affect the fungus type choice. Both the level of colonization and the fungal skin significantly impact how the fungal sheet material behaves mechanically in terms of stiffness, elasticity, and water-repellent properties (Aiduang et al. 2022b). White-rot fungi, such as those in the *Ganoderma*, *Pleurotus* genera, and *Trametes* of the phylum Basidiomycota, are often used because they have a high level of colonization and can grow on a variety of organic materials (Manan et al. 2021). Bae et al. (2021) investigated 64 strains of Polyporales. They found that *Ganoderma lucidum* was the perfect candidate since it demonstrated rapid mycelial growth and strong mycelium in both solid and liquid media (Bae et al. 2021). While some Polyporales had good mycelial development, their mycelial mats lacked physical sturdiness.

MycoWorks and Ecovative Design were the first US companies to obtain patents for these fungus-based leather technologies. Commercial leather products made from fungus first debuted on the market in 2022.

Mycelium-derived composites

Ongoing research and development in sustainable building materials has led to the emergence of mycelium as a viable and sustainable alternative in multiple industries (Alemu et al. 2022; Elsacker et al. 2022; Balaeș et al. 2023; Bonenberg et al. 2023). Mycelium-bound composites (MBC) are formed when mycelium grows on agricultural waste such as corn husks, straw, sawdust, or even textile waste (Girometta et al. 2019; Jędrzejczak et al. 2021). Fungus forms a fine network of threads that acts as a binding agent for the composite material. Once the mycelium has colonized the substrate, composites can be moulded into various shapes and forms, making them versatile for manufacturing products (Aiduang et al. 2022a). Non-processed MBC resembles the structural features of polystyrene and polyurethane foams (Jones et al. 2017) and finds application as non-structural applications as excellent thermal and acoustic insulators (Shakir et al. 2020; Gou et al. 2021).

Mycelial-bound composites are eco-friendly, require minimal energy input for growth, and are biodegradable. These materials have been explored for various applications, including packaging materials, construction materials, insulation, and even fashion items, and have the potential to replace traditional, less sustainable options made from synthetic polymers or other non-renewable resources (Alemu et al. 2022). One of the key advantages of mycelial-bound composites is their ability to decompose naturally, reducing environmental impact compared to traditional materials that may persist in the environment for a long time (Van Wylick et al. 2022). Therefore, using mycelium in biocomposites aligns with the broader goal of creating more sustainable and eco-friendly alternatives in response to environmental concerns. Several input parameters influence the final qualities of the mycelium-based material during production (Appels et al. 2019; Girometta et al. 2019). The precise selection of fungi, nutrient substrates, growing conditions, processing techniques, and additives significantly impact the characteristics of pure mycelium and mycelium-based goods. Water resistance and appearance are a few of the desired qualities (Elsacker et al. 2020).

Factors affecting the mycelium derived design

Mycelium source

Different strains of fungi used to create mycelium-based products affect the properties of the final composite (Alaneme et al. 2023). After inoculation, the hyphae grow inside the substrate matrix, forming a tight network that replaces the substrate. The resulting mycelium can firmly cement the substrate, creating a solid and lightweight biocomposite similar to expanded polystyrene (Lelivelt et al. 2015). Filamentous species that cause white rot are often used to grow mycelium-based materials, and these fungi can adapt to various situations. Interestingly, they can turn harmful substances like terpenes into non-toxic feeding substrates (Lee et al. 2015).

Each fungus has unique hyphal system that comprises different types of hyphae. The three most common types of hyphae are the skeleton, binding, and generative types. These hyphae range from straight to single-branched (generative hyphae), from thick-walled to solid straight elements (skeletal hyphae) with a few branches (skeleto-binding hyphae), to generously branching elements with twisted and contorted branches (binding hyphae). The "mitic" system refers to a species' variety of hyphal forms. There are three types of hyphal systems: (1) monomitic, (2) dimitic, and (3) trimitic. A monomitic hyphal system only shows generative hyphae instead of generative, skeletal, and binding hyphae in a trimitic hyphal system. Dimitic hyphal systems also exhibit skeletal or skeleto-binding hyphae (Porter and Naleway 2022).

Depending on their ability to break down lignin or cellulose, wood fungi are either white rot or brown rot. These organisms have the unique capacity to grow and derive energy from the intricate chemical structure of wood owing to their very active degradative mechanisms (Schmidt et al. 2012). Basidiomycota members are the most effective species for creating the best mycelial matrices (Lelivelt et al. 2015). For example, *Trametes multicolor* formed a velvety soft skin at the substrate surface with a flexible and foam-like structure, while *Pleurotus ostreatus* produced a stiff, rough surface substance when grown on rapeseed straw (Appels et al. 2019). An additional study found that the bending strength of *Ganoderma* grown on biomass from cotton plants ranged from 7 to 26 kPa (Ziegler et al. 2016). When grown on cellulose, *P. ostreatus* produced a more rigid material than *G. lucidum*. However, by adding dextrose to the growing medium, both fungal-based composites exhibited enhanced elasticity (Haneef et al. 2017).

Many fungi species have been used or mentioned in patents for mycelial-material applications as of the current date (Elsacker et al. 2020). Their mycelia function as a network of biopolymers whose mechanical properties depend on how each hyphae behaves individually, the network's orientation, and its connectedness (Islam et al. 2017). These many hyphal system topologies are represented in the physical properties of basidiomes, such as their hardness, consistency, or flexibility. Different fungi produce different hyphal structures like thin-walled hyaline clamped generative hyphae (*P. ostreatus*), digitiform lateral branched short generative hyphae, thick-walled septate generative hyphae (*Nothophellinus andinopatagonicus*), thick-walled skeleto-binding hyphae, and thick-walled clamped generative hyphae (*Ganoderma austral*), multi-branched thick-walled hyaline skeletal hyphae (*Funalia trogii*). The fungus that forms an elaborate network of thick-walled, branched, skeleto-binding hyphae produces a stiff structure in a lignocellulosic substrate and a tenacious layer in an agarized medium (Aquino et al. 2022). The Basidiomycota's mono-, di-, and trimitic hyphal networks illustrate how innate biological characteristics affect mycelial density (Jones et al. 2017).

Ganoderma species are commonly used in mycelium-based composites because they grow quickly and use organic waste as substrates. *G. lucidum* has high elasticity and is ideal for packaging and building materials. Additionally, *Ganoderma* species can form a dense, fibrous mycelium film (Sydor et al. 2022). But *Ganoderma* spp. also has some disadvantages, e.g., excessive hygroscopicity, low tensile strength, susceptibility to biological corrosion, and the need to deactivate the fungus (Sydor et al. 2022). When using *Ganoderma* fungi for composite production, addressing potential pathogenicity concerns is essential. The problem can be mitigated by selecting fungi that are not harmful to humans, animals, and plants, fungi that don't produce mycotoxins, and using spore-less strains. Killing the fungus in the mycelium material before leaving the facility and confirming the efficacy of the killing procedure are other options. By selecting appropriate fungi species, identifying fungi through standardized procedures, and conducting a risk assessment, mycelium-based composites can be produced safely for various applications (Van Den Brandhof and Wösten 2022).

Substrates and supplements

The type of substrate used for mycelium growth plays a significant role in determining the qualities of the resulting material (Alemu et al. 2022). Mycelium-based composites can be grown on various organic substrates, such as straw, sawdust, fibres, and agricultural waste streams (Holt et al. 2012; Pelkmans et al. 2016; Jones et al. 2017). Using biological waste as a substrate is a significant advantage of biocomposites (Girometta et al. 2019). The natural fibres in the substrate provide strain-hardening properties, making mycelium-based materials more robust and more resistant to shear failure. The choice of organic substrate impacts the quality of the final bulk material, as the properties of mycelium materials can be modified by changing the feeding substrates (Yang et al. 2017). Fungi degrade lignin, cellulose, and hemicellulose using two different enzyme systems: a hydrolytic system that breaks down polysaccharides using hydrolases and a particular degradative-oxidative extracellular system that degrades lignin and oxidizes the phenolic units (Sánchez 2009). Mycelium-material characteristics correlate with their nutritional sources, and the substrate used as nutrients impact the final quality of the bulk material. For instance, materials made of straw are more rigid than those made of cotton.

Contrary to cotton-based composites, straw-based materials are less moisture-resistant. A densely packed substrate produces composites with higher densities, elastic moduli, and compressive strengths than a loosely packed substrate (Appels et al. 2019). Composites made from oak sawdust showed higher tensile strength than those of beech sawdust (Faruk et al. 2014). The compressive strength of *P. ostreatus* mycelia composites formed using straw, sawdust, and mixtures of both substrates were compared. The strength of straw and straw plus sawdust did not significantly differ, suggesting that straw had a more significant influence on the composites' compressive strength. The mycelial composite of straw is naturally more elastic and regains its previous shape and height, which can be used to make foam alternatives (Ghazvinian et al. 2019).

Cellulose in the composite promotes burning, while lignin inhibits it (Dorez et al. 2014). The feeding substrate impacts the final composition of the composite, and different custom composites with desirable properties can form by varying the feeding substrate. A study indicated that *P. ostreatus* grew on potato dextrose frequently exhibited collapsed hyphae, narrow hyphae, and less chitin than those grown on cellulose. Low polysaccharides/chitin ratio synthetic material demonstrated poor Young's modulus, high water absorption, and high elongation rate (Haneef et al. 2017). Growing *P. ostreatus* and *G. lucidum* created a hydrophobic mycelium composite on cellulose and cellulose potato-dextrose. Fungus grown on cellulose exhibited higher levels of chitin, higher Young's modulus, and lower elongation than fungus grown on dextrose-containing substrates. The cellulose potato dextrose-fed fungus produced softer composite materials than those fed cellulose due to the higher percentage of lipids or proteins, which can function as plasticisers. The inference from the above mentioned research implies that filamentous components become more rigid when the feeding substrate is more challenging to digest. They found that the feeding substrate impacted the final composition of the composite and that different, custom composites with desirable properties could form by varying the feeding substrate (Haneef et al. 2017). Aquino et al. (2022) created composite discs by infecting poplar sawdust substrate with five different fungi (*P. ostreatus, Nothophellinus andinopatagonicus, Funalia trogii, G. austral*, and *Ryvardenia cretacea*). Only *G. austral* created the best composite, whereas *R. cretacea* had no successful substrate colonisation (Aquino et al. 2022).

Previously, composites made from lignocelluloses were produced using resin binders that were hazardous, fossil-derived, and required a lot of energy to create. These resins had formaldehyde, which could be harmful (Kariuki et al. 2019). The bonding of hyphae with the substrate in mycelium composites was also relatively weak, leading to weak mechanical strength. However, this can be improved by adding organic additives such as latex, which was used as a binder (He et al. 2014). He et al. (2014) found that by adding less than 5% latex and silane coupling agents, the growth of mycelium was not negatively affected, and the composite strength was significantly improved. Ghazvinian et al. (2019) found that when sawdust was supplemented with wheat bran, the resulting substrate had a lower density and improved mycelium growth, affecting tensile properties. Elsacker et al. (2020) also used bacterial cellulose as an additive in a study with white-rot fungus *Trametes versicolor*. They created pure bacterial cellulose sheets by culturing *Komagataei bacterxylinus* and then mechanically disintegrated them before mixing them with hemp substrate (Elsacker et al. 2020). After seeding the substrate with fungus and allowing mycelium growth, the resulting samples were heat compressed at 70 °C or 200 °C to create particle board samples with enhanced internal binding and tuneable mechanical characteristics. Finally, cellulose nanofibrils with a high surface area were found to mechanically interlock with natural fibres by hydrogen bonding, which gives the composites their structural stability.

Ly and Jitjak (2022) conducted a study using *Lentinus squarrosulus* to colonize three substrates: rice husk, coconut husk, and rice straw. Their findings showed that the rice straw composite had the highest compressive strength value and the greatest biodegradability, as indicated by the highest weight loss. Saini et al. (2023) investigated the potential of *P. ostreatus* to grow on textile residues containing white and coloured cotton and polyester mixtures. They obtained a lightweight biocomposite material with compressive strength ranging from 100 to 270 kPa. These findings suggest that the fungus can thrive on polyester plastic in textiles and can be an alternative method for converting this plastic material into bio-based materials. Balaeş et al. (2023) found that a RECOSOL73 strain of *Abortiporus biennis* when grown on a mixture of sawdust and wheat bran, developed a strongly hydrophobic surface material, had a density as low as 0.255 g per cm^3 and showed strong resistance. The hydrophobicity of the material makes it a promising candidate for producing biodegradable packaging items.

Growth parameters

The optimum environment for fungal growth varies depending on the species and the surface on which it grows. For example, the ideal incubation temperature for different fungi ranges from 21 to 30 °C, while the optimal humidity varies from 70 to 100%. The ideal pH range for most fungi is between 5 and 8 (Haneef et al. 2017; Appels et al. 2019). The incubation time for fungal strains can vary from 1 to 6 weeks, depending on the size and type of substrate (Jiang et al. 2013; Haneef et al. 2017). A more extended incubation usually results in a more thermally stable and less porous material with increased strength. As the mycelium grows, it fills the crevices between the fibres, making the fibre more firmly connected and increasing the overall density. However, a prolonged incubation period may cause complete substrate degradation, which can improve the elastic stiffness and reduce the shearing behaviour of the biocomposites (Yang et al. 2017). Maintaining a high level of carbon dioxide is essential to avoid the formation of fruiting bodies and to ensure efficient mycelium growth (Lelivelt et al. 2015). Chang et al. (2019) suggested a biological method to control the production of fruiting bodies. Using GSK-3 inhibitors in the cultivation medium inhibits the *Pleurotus djmour* strain's ability to produce fruiting bodies, promoting mycelium growth (Chang et al. 2019). This method is simple, economical, and reliable. Light and carbon dioxide also affect the density of the material, with high-density materials produced in low-carbon dioxide conditions in the dark and low-density materials produced in high-carbon dioxide environments in the light (Appels et al. 2019; Alemu et al. 2022).

Mycelial composite production systems

Mycelial biocomposites comprise 95% lignocellulosic material and 5% fungal mycelium (Jones et al. 2020; Haneef et al. 2017). These composites contain proteins, glucans, chitin, cellulose, tannin, cutin, lignin, lipids, and carbohydrates (Yang et al. 2021; Aiduang et al. 2022a, b; Sydor et al. 2022; Meyer et al. 2020). Although they offer environmental benefits, the diversity of fungal species and substrates used in their production poses challenges to standardization.

The process of producing mycelial bio-polymers begins with multiple containers. Each container holds a soft scrim, a nutritional substrate, and a specific fungal strain. These containers are then placed into a closed incubation chamber with directed airflow, and the temperature and humidity are set to the target level. This specific culturing method efficiently produces mycelial biomass and allows precise growth process control (Kaplan-Bie et al. 2022; Greetham

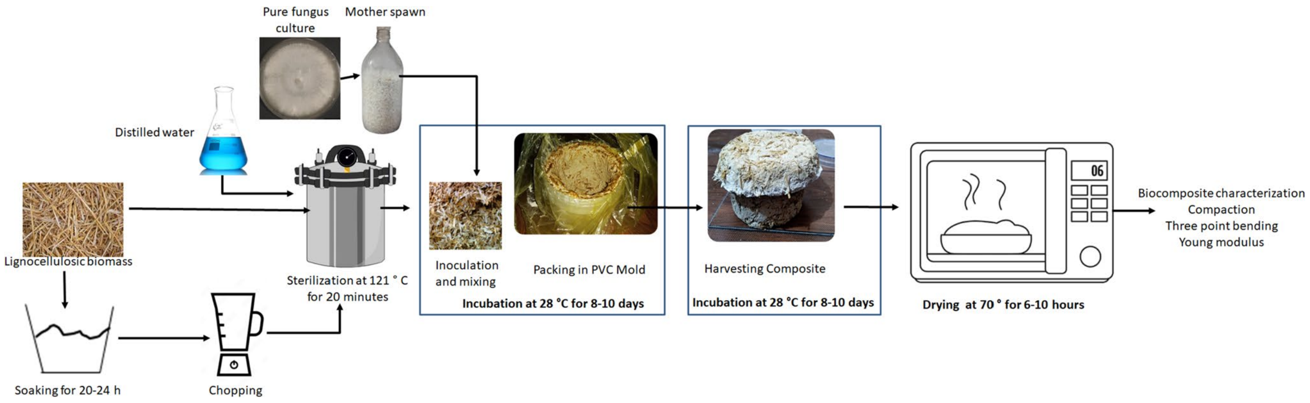

Fig. 1 Biofabrication process of mycelium-based composites

et al. 2022) (Fig. 1). The VTT Technical Research Centre in Finland has demonstrated the potential for mass-producing mycelial bio-polymer through continuous PMM production using bioreactor fermentation (Szilvay et al. 2020).

Mycelium-based composites (MBCs) have mechanical properties similar to wood and cork and can be rigid or pliable (Appel et al. 2019). The strength of the MBC can be controlled by adjusting the balance between the mass of the substrate and the mycelial mass. This balance enables the creation of versatile composites with tuneable density and porosity (Holt et al. 2012). Different substrates can be used to maximize the growth of mycelium. The substrate's nutritional profile affects the material's density, as a higher proportion of grains typically corresponds to a higher material density (Yang et al. 2021). The use and customization of substrates can be tailored to achieve the desired properties in the final material, depending on the desired material profile and field of application. Techniques such as submerged fermentation (SmF) and solid-state fermentation (SSF) are generally used to cultivate fungi and develop composite materials at the laboratory scale (Lübeck and Lübeck 2022; Jones et al. 2020). These materials can then be scaled up for industrial applications. Mycelium-bound composites are created through bio-fabrication, using fungal mycelium to grow on substrates (Alemu et al. 2022). For example, *Fomes fomentarius,* a type of basidiomycete, has been established to produce composite materials in industrial settings (Pohl et al. 2022). Mycelium from edible and medicinal fungi like *G. lucidum* and *P. ostreatus* has also been studied for creating tuneable and customizable materials with desirable mechanical properties (Haneef et al. 2017).

MBCs are developed using filamentous fungi, primarily at the laboratory stage, to create biocompatible materials from lignocellulosic waste and fungal mycelium. Once proven effective, these methods can be scaled up for industrial applications. One example involves the production of MBC using a more complex process (Schaak 2019; Dessi-Olive 2022), wherein a bacterial species is combined with a fungal species, non-nutritional substrates, and additional nutritional materials. In this approach, the bacteria provide mechanical properties to the bio-composite material through its metabolic process, and the fungal species binds it.

Post-processing

Mycelium-based materials have limited load-bearing structural elements (Bitting et al. 2022). Therefore, it is crucial to consider structurally informed geometry and appropriate digital fabrication methods when using mycelium-based materials due to their comparatively low structural load capacity.Various fabrication parameters impact the properties of mycelium-based materials, including their shape, density, flexibility, hydrophobicity, tensile strength, and mechanical and moisture absorption properties. By carefully selecting these parameters, the qualities of mycelium-based materials can be modified to suit various applications (Houette et al. 2022). Mycelium can be shaped and grown inside a scaffold during colonisation to achieve the desired shape. The mycelium can either be killed at 60 °C or left at room temperature, preserving its potential for future development (Attias et al. 2019).

Several processing techniques, including laser cutting, cold and heat compression, drying, and baking, can be used to achieve the desired shape and structure of the growing material (Jiang 2015; Yang et al. 2017). The temperature used for pressing after synthesis significantly affects the mechanical, physical, and thermal characteristics of mycelium-based materials. Cold or heat pressing can enhance the structural properties of mycelium-based composites, reduce porosity, and increase material density. Moreover, it facilitates the horizontal reorientation of fibres in a plane while reducing their thickness (Thoemen and Humphrey 2003). A combination of mycelium with polysaccharide-based substrates of different compositions has been designed to attain fibrous films with various properties. Two white-rot fungal species, namely, *G. lucidum* and *P. ostreatus*, were fed on cellulose and potato dextrose broth (PDB) supplemented with cellulose and later baked at 60 °C. Since the two feeding substrates share a common polysaccharide nature, it is expected that the mycelium would use similar fungal enzymes to hydrolyse them. The homogeneity of the two substrates resulted in the formation of uniform fibrous materials with tuneable and controlled structural and mechanical properties. Analysis of fibrous mycelium materials grown on the two substrates revealed that the ones formed on amorphous cellulose, which was hard to digest compared to PDB, were mechanically more robust and exhibited higher Young's modulus. When compared to natural-sourced materials, these fibrous mycelium materials exhibited high hydrophobicity (Haneef et al. 2017).

Heat-pressed mycelium-based composites resemble particle board and medium-density fibre board (MDF), possess densities and elastic moduli similar to natural wood, and are more robust, stiffer, and homogeneous. The cured but unpressed material forms a foam-like material. Three-point bending demonstrates increased flexural strength from hot-pressed > cold-pressed > unpressed materials. Although the organic substrate particles immediately stiffen the material at high strain, the composite's mycelium matrix undergoes mild compression at low strain (Appels et al. 2019). The pressing temperature significantly influences the mechanical characteristics of mycelial composites (Liu et al. 2019). Composites made by heat pressing exhibited higher stiffness, bending properties, and lower rupture strain when compared to *P. ostreatus*-rapeseed straw composites made by cold pressing, which had lower stiffness and tensile strength. Heat pressing increased the density of *P. ostreatus*-rapeseed straw composites by three times, and the thickness of the composite was uniform (Appels et al. 2019). However, it may lower the composites' thermal breakdown temperature, although it increases the thermostability of the siliceous layer, indicating that it can make fire-resistant materials (Liu et al. 2019). *G. lucidum* and cotton stalk heated at 200 °C and heat-pressed created material with 4.6 MPa rupture modulus, 680 MPa elasticity modulus, and 0.18 MPa internal bonding strength. The creation of hydrogen bonds during esterification, polymerization, and high pressing temperature is responsible for the composite's improved properties (Liu et al. 2019). The hydroxyl groups of the substrate's cellulose nanofibrils interacting with the cross-linkers or radicals during the fungus-induced breakdown of the substrate could be one reason for the formation of hydrogen bonding at higher temperatures (Widsten et al. 2006). Lignin is repolymerised at a pressing temperature of 200 °C by free radicals and acidolysis. Amino acid esterification in the substrate and mycelium improves interfacial adhesion (Liu et al. 2019). *Aspergillus niger* mycelium biomass-derived chitosan films underwent structural reorganization and lost solubility due to amidation after being heated (Solodovnik et al. 2017). Antinori et al. (2020) found that even minor changes in the PDB's composition could cause significant alterations in the morphology, hydrodynamics, and chemical properties of *G. lucidum* mycelium. According to Houette et al. (2022), compacted baked composites formed on a microparticle substrate had the highest elastic modulus during compression and flexural testing (Houette et al. 2022). Table 1 summarizes the mechanical properties of various mycelial-based materials created on different substrates.

Application

The twentieth century witnessed a lot of inventions in packaging materials, but most of them caused environmental pollution (Ncube et al. 2020; Wang et al. 2022). Mycelium-based polymers can be a sustainable, affordable, and environmentally friendly alternative to petroleum-based plastics (Abhijith et al. 2018). Ecovative Design LLC, a bio-composite materials company in Green Island, New York, is creating mushroom-based products to replace plastics and polystyrene foams for packaging, construction materials, and other uses. These mycelium-based products can be used for foam structures, styrofoam alternatives, mycelium bricks, furniture, structural frameworks, thermal and acoustic insulation panels, textiles, leather, and pharmaceuticals (Parkes and Dickie 2013; Jones et al. 2017; Yang et al. 2017) (Table 2). The foam insulation, wood and plastic panels, door cores, flooring, and furniture may all be replaced with these mycelium-based items. Much data has been accumulated on several patents on using fungi as a source for creative bio-based materials and given in Fig. 2 (Cerimi et al. 2019).

Mycelium-based goods are low-energy building materials that significantly aid in waste recycling (Madurwar et al. 2013). They have several advantages over traditional materials, such as cost, biodegradability, lower emissions, and lightweight. Combining a wide range of substrates with precise processing techniques makes it feasible to produce mycelium-derived materials with the desired structure and function for specific applications. For instance, straw/fibre-based mycelium composites can function as natural insulators due to their low density and low thermal conductivity (Uysal et al. 2004; Collet and Pretot 2014). These materials have lower thermal conductivity due to more dry air in the free-air gaps. It is very promising to employ mycelium biofoams as an alternative to traditional insulating materials for building and infrastructure development (Yang et al. 2017; Bruscato et al. 2019). Mycelium biofoams can be an alternative to conventional insulating materials for building and infrastructure development. These biocomposites can absorb around 75% of low-frequency

Table 1 Effect of substrate on the mechanical properties of various mycelium based biocomposites

Fungus	Substrate	Material Type	Density (g/cm^3)	Tensile Strength (MPa)	Flexural strength (MPa)	Compressive strength (MPa)	Young Modulus (MPa)
Pleurotus sp. (López Nava et al. 2016)	*Triticum* sp. & edible films	Mycelium based Foam	178.7–198.9	0.0499	0.004–0.018	0.020–0.060	
Mycelium	Hemp pith and cotton mat	Mycelium-based sandwich composite	0.10–0.14	0.1–0.2	–	0.670–1.180	66.14–71.77
Mycelium (Jiang 2015)	Flax	Mycelium Based Sandwich composites	–	0.035	–	–	–
	Jute		–	0.016	–	–	–
Mycelium (Islam et al. 2017; Silverman et al. 2020)	-	Mycelial based Foam	0.029–0.045	0.1–0.3	–	0.040–0.080	0.6–2.0
	Psyllium husk	Mycelial based Foam	0.29–0.35	–	–	0.156–0.340	–
Trametes multicolour (Appels et al. 2019)	Beech sawdust and rapeseed straw	Mycelial based composites	0.10– 0.39	0.010–0.240	0.050–0.87	–	2–97
Pleurotus ostreatus (Ghazvinian et al. 2019)	Saw Dust	Mycelium-based bio-composites	0.552	1.018	–	–	–
	Saw Dust + wheat Bran		0.493	1.380	–	–	–
Trametes versicolor (Zimele et al. 2020)	Wood chips	Mycelium-based biocomposites	179		0.11	0.52	–
	Hemp shives		134	0.04	0.16	0.36	–
Trametes versicolor (Jones et al. 2020)	Rapeseed straw	Mycelium-bound composites	–	0.04	0.22	–	–
Pleurotusostreatus (Jones et al. 2020)	Rapeseed straw	Mycelium-bound composites	–	0.01	0.06	–	–
Ganodermaresinaceum (Angelova et al. 2021)	Rose flowers	Mycelium-based bio-composites	462	–	–	1.029	–
	Lavender straw waste		347	–	–	0.718	–
Ganoderma lucidum (Chan et al. 2021)	Sawdust + empty fruit bunch	Dense mycelium-bound composites	239	0.81	1.62	2.21	286.1
Trametes versicolor (Elsacker et al. 2020)	Bacterial cellulose	Mycelium Based composites	456.82	–	–	0.056	0.007GPa
Pleurotus ostreatus (Vašatko et al. 2022)	Beech sawdust	Mycelium-based biocomposites	0.27	–	–	4.310	0.1432
Pleurotus ostreatus (Alemu et al. 2022)	Potato dextrose agar (PDA) + sawdust	Mycoblock	343.44	–	–	0.750	–

(1500 Hz) sound waves, which can be used as construction material for noise-cancelling buildings in metropolitan cities and noisy industrial areas (Pelletier et al. 2013). As the acoustic wave travels through the material's numerous pathways and gets converted to heat, the fibres in such composites act as frictional elements and may reduce the wave's amplitude (Peters 2013). Thin fibres are more acoustically absorbent due to their ease of movement, but a large density of fibres

Table 2 Major mycelial biocomposites and their application in various industries

Product Category	Uses	References
Mycelium leather	Textiles, apparel, footwear, bags and accessories e.g. *MycoWorks; Mycelium Textiles* (*Tartan mycelium)*; *Mycelium lace*; *Mycelium velvet*	Ross (2014), Collet (2017)
Mycelium based foams	Packaging material as an alternative to traditional packaging materials like Styrofoam e.g. *MycoFoam* (corn husks); *EcoCradle* (Ecovative Design LLC -Ecovative)	Holt et al. (2012), Abhijith et al. (2018), Appels et al. (2019
Mycelium Based Composites	mycelium bricks, furniture, structural frameworks, thermal and acoustic insulation panels, fabrics, leather, medicine, timber and plastic insulation, door cores, panels, flooring, furniture and furnishings e g. *MycoFlex*™;*MycoComposite*™; *Mycotecture; Mycotecture Alpha; Mycelium + Timber* series; *MycoTree; Mycelium Chair*	Parkes and Dickie (2013), Pelletier et al. (2013), Ziegler et al. (2016), Jones et al. (2017), Yang et al. (2017), Cerimi et al. (2019), MoK (2019)
Biomedical patches and platforms	Curcumin-loaded mycelium-based antimicrobial wound healing patch Tissue engineering adhesion platforms	Khamrai et al. (2018), Narayanan et al. (2020), Wang et al. (2020), Antinori et al. (2021)

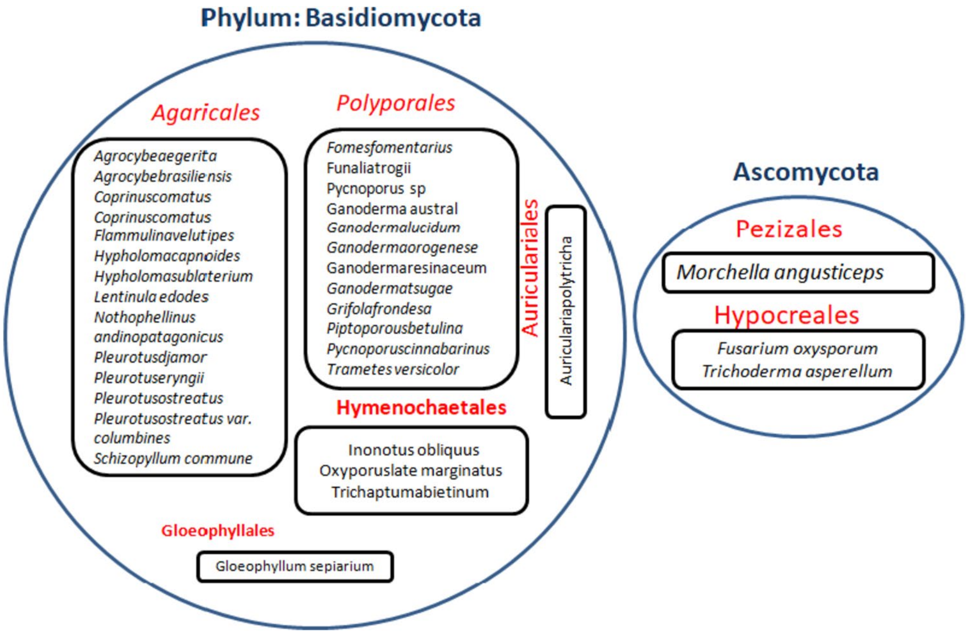

Fig. 2 Different types of fungi belonging to various phyla cited in patents for mycelial biocomposites synthesis

per unit volume produces more twisting paths and increases airflow resistance (Jailani et al. 2004). Mycelium-based materials' surface porosity and shape are crucial factors in sound absorption. Less porous materials perform significantly better at sound attenuation than highly porous ones (Samsudin et al. 2016). Mycelium-based materials are non-flammable compared to petroleum-based materials, produce less carbon dioxide, and take longer to spread flame over (Jones et al. 2019). Thus, they are a practical, affordable, safe, and ecologically friendly substitute for conventional building materials. Designers work at the nexus of biology and design, illustrating how they can influence the development of novel materials in an interdisciplinary setting. While mycelium-based composites are emerging as a viable substitute, there is still more to learn about their mechanical characteristics.

Challenges associated with biocomposite production

Upscaling mycelial biocomposite production has many challenges that must be addressed to ensure its scalability and viability in various sectors. The main challenges are mentioned below.

- A lack of consistent standards and protocols makes reproducing results and maintaining quality control difficult (Bitting et al. 2022).
- Selecting suitable substrates and fine-tuning their composition to achieve desired properties remains a significant challenge (Alaneme et al. 2023).
- Enhancing the durability and longevity of mycelium-based composites while maintaining their biodegradable nature requires careful consideration (Butu et al. 2020).
- Reducing costs to make these materials competitive with existing alternatives is essential for widespread adoption (Butu et al. 2020).
- Transitioning from laboratory-scale production to full-scale industrial manufacturing necessitates efficient and reliable automated systems (Bitting et al. 2022).
- Controlling moisture levels throughout the growth and post-processing stages is critical for achieving optimal performance (Yang et al. 2021).
- Establishing robust testing and certification frameworks to guarantee product safety and reliability is necessary for market acceptance (Bitting et al. 2022).
- Bridging the gap between academic research and industrial practice is vital for advancing knowledge and promoting innovation (Bitting et al. 2022).

By overcoming these challenges, developing mycelium-based composites as viable alternatives to traditional materials in various industries can be achieved. This will contribute to sustainability efforts and foster economic growth.

Future prospects

Mycelium has gained attention for its ability to grow and form tuneable structures, making it a potential alternative to traditional materials in industries such as construction, packaging, and even fashion. In the future, mycelium-based composites can create lightweight and sturdy building materials that replace traditional materials like plastic or insulation. They can be used for packaging as an eco-friendly alternative to conventional plastic, as they can be grown into specific shapes and then dried to create a biodegradable packaging material. Mycelium-based products like myco-leather are gaining popularity due to their biodegradable nature and circular production process. They have diverse applications beyond traditional composites, including wound care and biomedical scaffolds (Ruggeri et al. 2023). Engineered melanin-producing mycelium can provide antioxidant properties and a self-growing radiation shield for deep-space exploration (Vandelook et al. 2021). As some fungi can break down and absorb contaminants, mycelial-driven design could be employed in environmental remediation projects to help clean up polluted areas (Vaksmaa et al. 2023). Ongoing research may uncover new applications and improvements in mycelial-driven design, expanding its potential uses. However, it is -necessary to note that the development and adoption of mycelial-driven design depends on various factors, including technological advancements, market demand, regulatory considerations, and public acceptance. The versatility and sustainability of these materials make them a promising next-generation biomaterial.

Conclusion

Sustainability has become an essential aspect of our lives today. Mycelial biocomposites provide a sustainable alternative to traditional materials derived from non-renewable resources. Additionally, these biocomposites have the potential to biodegrade naturally, which reduces their environmental impact. Biocomposites are versatile and can be adapted to various applications such as packaging, construction, and consumer goods. This versatility makes them suitable for replacing non-biodegradable materials, thus aligning them with the global focus on circular economies and waste reduction.Continued research and development efforts will likely lead to technological advancements addressing current challenges. These technological advancements involve refining production processes, improving material properties, and enhancing scalability. Increased investment and interest from industries may drive the commercialization of mycelial biocomposites. The cost-effective and efficient production methods will make these materials widely adopted in various sectors. Educating consumers and businesses about the benefits of mycelial biocomposites will be crucial for market acceptance. Overcoming scepticism and demonstrating these materials' economic and environmental advantages will contribute to their successful integration into mainstream industries. Clear regulatory guidelines and support for sustainable materials could facilitate the adoption of mycelial biocomposites. Governments and international bodies may play a role in establishing standards and incentivizing environmentally friendly materials.Collaboration between researchers, industries, and policymakers will drive innovation in mycelial biocomposites. Cross-disciplinary approaches and partnerships can lead to material science, engineering, and application breakthroughs.

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