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Current State, Future Prospect and Challenges on Fungal Biomaterials: A Review

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Abstract

The durability of fungal mycelia as well as its sustainability and environment-friendliness make them of great interest for a wide variety of applications. This paper is expected to improve understanding of the use and integration of mycelium to produce sustainable and environmentally friendly biomaterials. These include replacing non-degradable plastics in packaging, an alternative to animal-based leather in fashion, durable and sturdy interior design, and eliminating CO_2 emissions in architecture and building designs. Many well-known companies have implemented these products in their sustainability and environmental campaigns. Fungal biomaterials still face challenges in product development, for example, producing non-destructible but functional biomaterials, especially in structural designs. Fungal biomaterials, however, will have many advantages in the future due to an increase in public awareness regarding sustainable and environmentally friendly products.

***Keywords**: Bio-Composite; Biodegradable; Fungal Biomaterials; Mycelium-Based Products; Sustainable Materials.*

Introduction

To prevent pollution of the environment, waste generation, and depletion of natural resources, society needs technological improvements. Commercial centers, the construction sector, households, agriculture, and industry are the main sources of environmental pollution. One of the main causes of pollution is improper waste recycling. Recycling technology will be the key to sustainable living in the future (Alemu et al., 2022). Construction materials and packaging are currently non-recyclable and unfriendly to the environment. During production, transportation, and dismantling, the use of these materials consumes energy, limits natural resources, and pollutes air, land, and water bodies. Recent studies suggest that bio-composite can be produced from fungal mycelium to replace conventional materials (Ghazvinian et al., 2019; Maximino C. Ongpeng et al., 2020).

A mycelium is a vegetative part of fungi with branched hyphae and a tube-shaped structure that is hollow (Islam et al., 2017). It creates a very dense network of threads by binding around organic substrates such as coffee husks, sawdust, wheat bran, straw, and sugarcane bagasse, thereby acting as a natural binder. In addition to its low cost, low density, and environmentally friendly properties, biomaterials have some of the main advantages over conventional synthetic materials (Elkhateeb and Daba 2019; Heisel et al., 2017; Travaglini et al., 2014). The Basidiomycota family of fungi has excellent fruiting bodies and a flexible mycelium structure (Haneef et al., 2017) Mycelia from this family has been utilized in many applications such as in packaging, fashion, architecture, and interior design. In this review, we will discuss the use and integration of mycelium to produce sustainable and environmentally friendly biomaterials. Also, we will discuss challenges that arise with fungi-based biomaterials.

Result and Discussion

The Characterization of Fungi

The divergence between fungus cells upon plant cells lies in the cell wall structure. The fungal cell wall is formed by chitin which is a polysaccharide that contains nitrogen that gives a vigorous but flexible structure (Labourel et al., 2020). In addition to chitin, the strong and sturdy structure of fungal cell walls is also a result of the presence of other substances such glucans, chitosan, and glycosylated proteins that later combine with polysaccharides to form glycoproteins (Garcia-Rubio et al., 2019). The phylum of fungi known as Basidiomycota has a variety of fungi that have been used in the manufacture of biomaterials. A class of fungi known as Basidiomycota has excellent fruiting bodies and a mycelium structure that is comparatively old and firm (Haneef et al., 2017). Aggregates of hyphae serve as the building blocks for fungal mycelium and serve as tools for consuming nutrients from the host. Hypha has a pipe-like structure that has specialized diameters on each species which is around 1-30 μm depending on the nutrient uptakes (Islam et al., 2017). From the flexibility of the hyphae, the structure can grow and develop into various forms according to the desired cultural media and then be produced on a large scale (Haneef et al., 2017). Each fungus species, however, plays a varied function in the production of biomaterials due to the varying density structures of its hyphae.

Fungal hyphae development is optimized by both the culture and planting media in use, as well as the hyphae structure. In a medium with more nutrients, hyphae will develop stronger and stiffer. The cellulose PDA media, wheat bran, sawdust, and sugarcane were found to provide the best hyphal growth conditions. As a result of structural studies using an SEM microscope, the hyphae morphology in mixed media grows with a thick and solid structure compared to the other four media. Besides producing mycelium, it is compact, dense, and does not have excessively large cavities, making it a suitable substrate for manufacturing biomaterials (Joshi et al., 2020).

Among the distinctive features that make the hyphae structure a biomaterial is the presence of hydrophobin proteins on the surface of its wall. A tiny protein called hydrophobin is responsible for facilitating gas exchange, spore dissemination, and fruit bodies as well as separating aerial hyphae with liquid media to reduce the surface tension of water and air (Kulkarni et al., 2020; Landeta-Salgado et al., 2021; Zhang et al., 2011). A factor used as a biomaterial is the hydrophobin protein's presence in the fungus structure. The previous study looked at the Δ*sc3* gene, one of the genes that make up the hydrophobin protein, and provides evidence in favor of this. The density and make-up of the cell wall are both influenced by the Δ*sc3* gene in *S. commune* fungus. The mycelium, which is employed as a bio-based material, becomes stronger, denser, and more compact when the Δ*sc3* gene is deleted, as evidenced by denser hyphae that don't have numerous voids (Appels et al., 2018).

Production of Mycelium-based Materials

In the process of creating a bio-composite, fungi are uniformly grown in small fragments of organic substances derived from agricultural residues or industrial by-products. During this process, fibers are generated as the mycelium network grows, connecting these fragments into a porous substance. It is well known that these entities, referred to as mycelium-based foams or mycelium bricks, are mechanically strong, lightweight, and environmentally friendly (Aiduang et al., 2022). Since fungi are preferentially able to degrade cellulose or lignin in plant biomass, mycelium is usually grown on agricultural crop waste, such as cotton, corn, wheat, hemp, and sawdust, which are lignocellulosic wastes. All hardwoods and crop wastes contain cellulose, the most abundant natural polymer (Yang et al., 2019). Fungal strain selection, media formulation, and processing techniques are important in obtaining distinct forms and material functionalities of the mycelium. As an example, MYCL used *Ganoderma*-based mycelium to produce mycelium leather Mylea™, but used *Trametes* strain to produce bio-composite. Both products use the same foundational substrate (Albizia sawdust, wheat bran, tapioca starch, and $CaCO_3$) but with different post-treatment processing techniques. The production process can be depicted in Figure 1, using the following steps: 1) The fungal spawn is prepared in a solid substrate; 2) Onto the sterile mixed media, the spawn is infused aseptically and grown at room temperature until it is fully colonized; 3) Bio-composite is grown in a mold or cast and dried, d) Bio-composite is hot-pressed and coated to prevent damage.

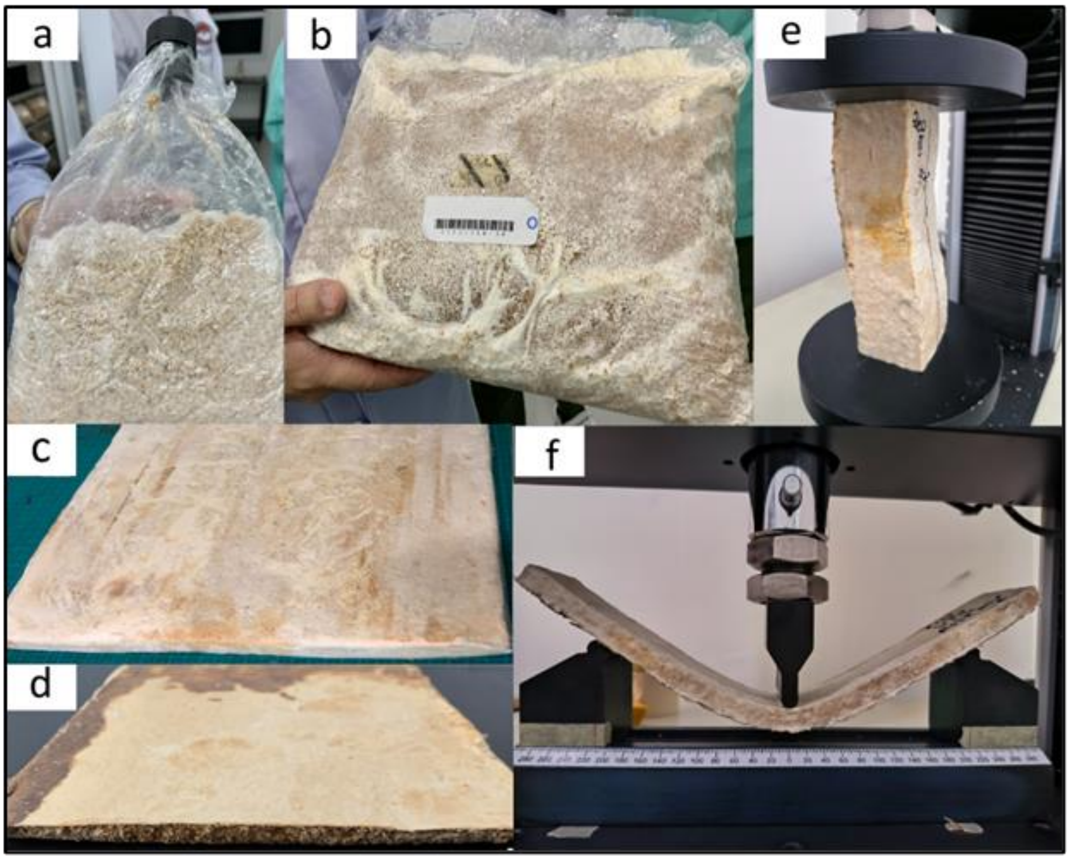

Figure 1. Bio-composite production and testing. a) Ganoderma sp. spawn, b) Fully colonized Ganoderma sp., grown in Albizia sawdust as the lignocellulosic substrate c) Bio-composite grown in a 30 x 30 cm cast and dried, d) Bio-composite after hot-pressed, e) Compressive strength measurement, f) Flexural strength measurement with 3-point bending test.

The bio-composite produced has a strength-to-weight ratio ranging from 350.39 to 683.61 and a flexural strength of 19010 kPa after being hot-pressed (Rahayu et al., unpublished data). For the mycelium-infused composite ideal for packaging and construction, compressive strength is a crucial attribute. It refers to how well a material or structure can withstand pressure when pressed together. Generally, flexural strength refers to the stress at which a sample breaks when bent. It is also referred to as the modulus of rupture, the bend strength, or the transverse rupture strength. Mycelium fibers will likely contribute to the composite's flexibility and it will only rupture under high strain as they are more elastic than colonized substrate particles. The authors believe that the tensile strength is not significantly affected by the species of substrate and fungi, but is affected by the pressing method, as heat pressing increases tensile strength significantly. In comparison with unpressed samples, hot-pressed bio-composites had an increased flexural strength of 4636 times (Rahayu et al., unpublished data).

Fungal Biomaterials for Packaging

Plastic raw materials were used in the past for packaging, as an alternative to paper produced from trees to reduce illegal logging. Plastics possess hydrophobic properties, can resist photolysis, and do not decompose (Holt et al., 2012). However, plastics come from petroleum mining, which is limited, non-renewable, difficult to decompose, and difficult to recycle, and plastic processing does not consider environmental sustainability (Ferreira-Filipe et al., 2021; Holt et al., 2012). As more people become aware of this fact, they have come up with alternative sources that are made from bio-based materials (Ferreira-Filipe et al., 2021). Table 1 summarizes consideration aspects of biological materials, including pros, cons, and solutions.

Table 1. Consideration aspects of biological materials (Ferreira-Filipe et al., 2021)

Pros	Cons	Solution
Natural materials	Expensive industrial costs	Biorefinery technology development (conversion of biomass into energy and beneficial by-products)
Degraded naturally	Mostly use GMOs (Genetically Modified Organisms)	Recycle regulation with GMO waste labeling
Less emission	Vulnerable to degradation by high temperature	Nanotechnology development to improve mechanical and physicochemical quality

A growing human population encourages the development of circular economy thinking that seeks to limit consumption and waste of resources such as water, energy, and materials while producing goods or services. Mushroom mycelium is one of the natural materials developed with advantages such as easy access, low production costs, low energy consumption, and low emission levels, naturally degraded, easy to recycle, flexibility to customize the fungal strain, substrate composition, incubation parameters, production procedure (Alemu et al., 2022; Bitting et al., 2022). Yet, mycelium also brings disadvantages such as hydrophilic, limited material reactivity, easy degradation in organic acids or low pH, and hygiene needs strict treatment (by drying or heating) (Alemu et al., 2022; Bakshia et al., 2020).

Two types of mycelia can be produced, namely PMM (Pure Mycelium Materials) and MBC (Mycelium-Bound Composites). PMM consists of mycelium without a solid substrate, usually cultured or produced using liquid substrates. On the other hand, MBC is mycelium bound to a substrate, usually cultivated or produced using solid substrates (Bitting et al., 2022). MBC requires the fungus to colonize, and the fungus requires a substrate to survive. Therefore, researchers take advantage of natural materials around us that have the potential for mycelium substrates, such as cotton carpels, husks, starch mixtures, sawdust, straw, bagasse, etc. (Alemu et al., 2022; Holt et al., 2012). For the manufacture of MBC, the fruiting bodies of mushrooms must be inhibited so that only the mycelium can grow. An inhibitor of glycogen synthase kinase-3 (GSK-3) can be added to mushrooms to inhibit fruiting bodies, such as lithium chloride (LiCl) or CHIR99021 trihydrochloride (Chang et al., 2019). Due to the presence of chitin in the fungus mycelium, which is an important component of substrate adhesion, fungi are also lignocellulosic degrading organisms, so they can be used as natural adhesives for organic substrates. It is important to note that the mycelium growth and chitin content of each mushroom species differ (Alemu et al., 2022). Mycelium will contain more chitin so that the texture is stiffer if the living substrate is difficult to digest (Haneef et al., 2017). The most widely used mushroom species that have a good assembly of mycelium are *Ganoderma* sp. (Holt et al., 2012), *Pleurotus ostreatus* (Alemu et al., 2022), *Trametes versicolor*, *Morchella* sp., *Xylaria* sp., *Polyporus* sp., and *Fomes* sp. (Cerimi et al., 2019). The results of the research have been applied by major computer manufacturers in the United States as packaging and laptop protectors (Holt et al., 2012) or for glassware protection as a substitute for polystyrene (Abhijith et al., 2018; Manan et al., 2021). Several analytical tests are performed, including compressive strength, flexural strength, modulus of elasticity, density, dimensional stability, accelerated aging, water absorption, cone calorimetry, and thermal conductivity (Holt et al., 2012).

As a natural degrading compound, chitin is odorless, non-toxic, amphiphilic (having a hydrophobic and a hydrophilic side), and relatively slow in degrading. Using chitosan as a packaging material is possible because chitin itself can be extracted into a more stable derivative product known as chitosan. In the packaging industry from recycled paper, chitosan can strengthen the structure of the recycled paper, making it smoother and more water resistant (Bakshia et al., 2020). The physicochemical properties, hydrophobicity, stability, and interactions of chitosan with other composite materials can all be improved with chitosan engineering. Divisions of fungi containing chitin can be explored in Ascomycota, Basidiomycota, Zygomycota, and Deuteromycota. The fungus can also be fermented to provide natural colors for food packaging, such as *Talaromyces* sp, of which *Talaromyces amestolkiae* is most commonly used (de Oliveira et al., 2020). These colorants from fungi are safer, compatible with packaging materials made from mycelium, and protecting food from contaminants.

Fungal Biomaterials for Fashion

Fast fashion is a phenomenon, where the latest trends and high levels of consumer demand affect the amount of fashion production (Zekri 2021). This affects the production chain system and the lifestyle of modern society, especially the generation Z and Y (millennials). The mass production that occurs causes the need for many resources and the use of low-quality (non-durable) materials to pursue trends and affordable prices. Plus, the lifestyle of modern society which tends to follow trends has led to a linear concept in fashion, namely take-wear-throw (Olsson et al., 2020). This system certainly has an impact on environmental damage, especially on materials that are difficult to decompose. This phenomenon has led to community innovations related to mushroom technology that produces mycelium as an environmentally friendly material as well as efforts made by a creative community in fashion management (Rognoli et al., 2022). Thus, it is hoped that the architecture can act as a container that supports activities by applying the cradle-to-cradle (upcycling) concept. This concept invites the public, especially modern society, to be more aware of the management and use of fashion which is supported by a metaphorical method approach of combining mushroom and fashion characters, as well as programs from processing mushrooms and fashion to create an activity center that has a positive impact on the environment and society by promoting ecological balance.

The activity program that is sought is of course related to the background of fashion and ecology, so here we use the program theory proposed by Bernard Tschumi, based on the need for space for activities that support to form of an architecture program (Charitonidou 2020). The application of the upcycling concept, which is to produce a flow of activities that occur based on the issue of fast fashion by using materials from production and excess consumption to be reprocessed into better fashion quality without producing waste, but processing waste by collaborating with mycelium materials as an alternative material that is more environmentally friendly and durable, so that it can be used and resold (Angelova et al., 2021).

Biomaterials are basic materials from biological materials; any substance (other than a drug) or a combination of substances, synthetic or natural, that can be used over a while, as part or as a whole system that treats, reproduces, or replaces any tissue, organ or function of the body (Suvaneeth and Nair 2018). Fashion biomaterials made from plant leaves, fruit waste, and microorganisms grown in the laboratory can replace textiles of animal origin including leather, fur, wool, and silk. Combed cotton material is the most widely used material, due to its soft texture and also its durable resistance and affordable material prices (Saratale et al., 2018). In a globally interconnected world, textiles such as leather sourced from cows, and wool sheared from sheep, have become a serious source of deforestation, other adverse land use impacts, biodiversity loss, and climate change, while fur farming (harvesting mink fur slaughtered animals, foxes, raccoons, and other wild animals kept in captivity) have become a major biohazard to human health a threat underscored by the risk that fur farming poses to the current and future spread of zoonotic diseases (Warwick et al., 2023).

Hermes released a bag made of mushroom skin. This luxury fashion house collaborated with MycoWorks to present leather bags that are more environmentally friendly. Mushroom skin is made of mycelium, a type of fiber that it uses to absorb food to carry out the process of vegetating mushrooms (Jones et al., 2021). The mycelium is then deliberately designed to form durable fibers that look and feel like real leather. Mushroom leather is not only an alternative to genuine leather, but can also be used as an alternative to synthetic leather. As we know, synthetic leather has so far been considered as a material or a substitute for animal skin. However, the manufacturing process is even more dangerous because it involves chemicals that can damage the environment (Jones et al., 2021). While mushroom skin is produced using natural resources, it is quickly produced and requires little water or other energy. That's what makes it a better choice of animal and synthetic leather substitutes. The mushroom used is lingzhi mushroom, which is the material of Mycotech's research to produce Mylea as an environmentally friendly alternative raw material, which is also located in Bandung, in the highlands which is a characteristic for mushroom cultivation (Arko et al., 2017). The mushroom character that has been mentioned previously, gives rise to a basic idea or a rough idea that still displays the mass with the impression that it is piled up and spread out both in terms of mass and circulation. The placement of rough zoning and organic shapes from mushrooms, as well as solid-void games, add to the fashion character while still thinking about the context around the Bandung area.

Fungal Biomaterials for Architecture and Interior Design

Architecture and interior design have been developed since the 8th century. At that time architectural and design applications used stone carvings to make buildings, statues, tables, chairs, temples, inscriptions, and even made an amphitheater known as the Colosseum in Italy. To make materials that are more durable and accessible, such as concrete, steel, wood, masonry, and stone, the construction and interior design industries have progressed over the past decade. The strength, weight, and durability of each vary, making them suitable for varied uses (Charpentier-Alfaro et al., 2023). Several places of worship in several countries in every religion (Islamic, Christian, Zoroastrian, and non-religious) have 5 construction materials, most of which are stone, brick, wood, tile, and adobe. Eventually, there are sustainable developments that approach eco-friendly materials due to having a similar structure, strong, lightweight, natural, degradable, and environmentally friendly (Almpani-Lekka et al., 2022). These materials are a brilliant idea for the development of architecture and interior design for the future.

In the fields of architecture and interior design, mushroom mycelium is frequently employed as a biomaterial. Because they are created from organic components, are biodegradable, accessible, and unlikely to become extinct, these biomaterials are viewed as a potential option for a future that stresses a sustainable environment. In comparison to commercially available thermoplastics used in the building and construction sector, mycelium-based composites perform well in terms of insulation and are safer and more fire-resistant (Jones et al., 2017) . According to European Union guidelines, all new construction should be virtually fully energy-free by 2020. Developments in the field of materials science have substantially assisted the changeover.

Biomaterials in this area have been produced by numerous startup businesses in various nations. MycoWorks has created synthetic leather that looks and feels like genuine leather using the mycelium of Reishi mushrooms, also known as *Ganoderma lucidum* and an agricultural waste. After that, the leather is utilized to create biomaterials like floor tiles and wall paneling for rooms. Officina Corpuscoli created kitchenware items using mycelium (without disclosing the type of mushroom it was) and collaborated with the MOGU company to create useful, creative materials. For instance, interior design, building, transportation, clothing, and furnishings. In order to replace conventional packaging materials, such as boards and food products, Ecovative devised and patented numerous procedures for producing mycelium goods. MYCL has created biomaterials for architecture, interior design, and fashion (Figure 2). Fashion items from MYCL have been displayed at renowned worldwide fashion events (Heisel et al., 2017).

Figure 2. Mycelium-based interior design (A) and fashion (B - E) products (presented in men.ja.mur exhibition July 7th – August 3rd 2022, Bandung, West Java)

Challenges in Fungal Biomaterials

Mycelium-based materials have shown their potential as a more circular and economically competitive alternative to conventional synthetic materials in various industries ranging from packaging, electronics prototyping, furniture, and fashion to architecture. However, the application of mycelium-based materials in the construction industry is still limited to several constraints. Mycelium has small-scale prototypes and architectural installations due to low mechanical properties, lack of standardization of production methods and material characterization (Bitting et al., 2022). Its relatively low structural load capacity means that the application of mycelium-based materials must be coupled with appropriate structural geometry and digital fabrication methods. A lack of general knowledge has also led to a lack of public awareness of the existence of such materials and a lack of confidence in their large-scale application beyond alternative packaging and consumer products (Jones et al., 2017). Limitations stemming from their typically foam-like mechanical properties, high water absorption, and numerous gaps in material properties documentation necessitate the use of mycelial composites as non- or semi-structural supplements to traditional construction materials for specific and appropriate applications, including insulation panels and furnishings (Jones et al., 2017).

A second distinction can be made between production approaches that kill the mycelium during the production process and approaches that try to preserve the mycelium as a living organism. In addition, there is a disconnect between industry and academia. Publications regarding new research and applications of mycelium-based materials tend to hide information and data regarding the fungal species used, incubation parameters, substrate composition, or detailed fabrication procedures, as most authors are affiliated with commercial companies (Attias et al., 2020).

Conclusion

The increased awareness of sustainable and environmentally friendly products will lead to many advantages for fungi biomaterials in the future. In this paper, we explored how mycelium can be used to produce sustainable and environmentally friendly biomaterials, including biodegradable packaging, leather-like fashion goods, durable and sturdy interior design, and eliminating CO_2 emissions from building and architecture design. Hopefully, the readers will gain a deeper understanding of how mycelium is used and integrated to create sustainable and environmentally friendly biomaterials.

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