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Sustainable Materials and Bioproducts from Mushrooms

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Introduction

Mushrooms, particularly fungal mycelium, are transforming sustainable materials and bioproducts with their unique properties and broad applications. Mycelium, the vegetative part of fungi, can grow on nutrient medium, agricultural or industrial waste, making it a renewable and biodegradable resource. It serves as a foundation for eco-friendly alternatives to plastics, leather and synthetic foams, addressing pollution and resource depletion. In packaging, mycelium-based composites replace non-biodegradable materials, while in modern fashion, they provide sustainable leather substitutes. The construction industry utilizes mycelium for insulation and lightweight building blocks, reducing carbon emissions. Beyond materials, mushrooms play a vital role in bioremediation, breaking down pollutants and transforming organic waste into fertilizers. Their adaptability extends to bioelectronics, where mycelium conductivity aids in creating biodegradable devices. These applications highlight the low-energy, sustainable processes of mushrooms, positioning them as essential tools for combating climate change and fostering a circular economy.

Mycelium-based materials and their application

Mycelium-based materials are emerging as a sustainable alternative across various industries, particularly in packaging, construction and textiles. These materials exhibit unique properties that make them suitable for diverse applications, including their biodegradability, mechanical strength, and thermal insulation capabilities. These materials are being adopted across multiple industries as sustainable alternatives to conventional materials that contribute to pollution and waste.

For the production of Trichoderma, we needed Trichoderma culture, talc powder, and jowar grains as a raw materials. The amount of Trichoderma culture that is produced in the laboratory increases by using jowar grain as a growth substrate. For that dip, soak the jowar grain in a 2% sucrose solution for 6 hours and then release the extra water present in the jowar. Take 250 gm of grain in sterilised polythene and cover the mouth with a cotton plug. And then autoclave the polythene at 15 psi for 30 to 40 min, take out the polythene from the autoclave, and allow it to maintain its natural temperature. Take 5 ml. of Trichoderma culture using a pipette from a 2×108 cfu/ml concentration and put the culture in polythene. Then seal the polythene with tape and put in BOD incubator at 25°C for 15 days, grind the grain in fine texture and mix with the talc powder in ratio of 1:9. Now the Trichoderma is ready to pack for further application.

1.Packaging: Mycelium-based materials are revolutionizing the packaging industry by replacing Styrofoam and single-use plastics. These composites are lightweight, durable and entirely compostable, making them ideal for protective packaging in electronics, food and fragile goods. Their low environmental footprint and biodegradability help address the global plastic pollution crisis (Joshi et al., 2020). The innovative use of mycelium in packaging aligns with the principles of a circular economy, where materials are designed to be reused and recycled, thereby minimizing environmental impact (Barta, 2024).

2.Construction: Mycelium composites are gaining attraction in construction for their unique characteristics, such as lightweight, thermal insulation and fire resistance. Used as insulation panels, bricks and structural components, these materials provide an eco-friendly alternative to traditional building materials like concrete and synthetic insulation, significantly reducing the carbon footprint of construction projects. Studies have shown that mycelium composites can act as effective CO_2 sinks, contributing to lower greenhouse gas emissions in the construction sector. Furthermore, the mechanical properties of mycelium composites can be tailored through the selection of substrates, allowing for customization based on specific structural requirements. The ability to produce these materials using agricultural and industrial waste further enhances their sustainability profile (Livne et al., 2022).

3.Textiles: Mycelium-based vegan leather is transforming the fashion and furniture industries. This cruelty-free alternative to animal leather is not only environmentally sustainable but also customizable in texture, appearance and durability. Used in clothing, accessories and upholstery, mycelium leather offers a luxurious feel with a fraction of the environmental impact of traditional leather tanning processes. This versatility allows for innovation in fashion and home textiles, promoting a shift towards more sustainable practices in the industry (Rathinamoorthy et al., 2023).

Bioplastics and polymers from mushrooms and their application:

Mushroom-derived materials, particularly chitin and glucan, are gaining attention for their potential to revolutionize the bioplastics and polymer industry. Extracted from the cell walls of fungi, these natural polymers are renewable, biodegradable and eco-friendly alternatives to conventional petroleum-based plastics, which are a major contributor to global plastic pollution. This capability is primarily due to the mycelium's unique biochemical composition, which includes polysaccharides, proteins and lipids, allowing it to form dense, cohesive structures that can be molded into various shapes.

1. **Packaging:** Mushroom-based bioplastics are ideal for creating sustainable packaging solutions, such as biodegradable containers, wraps and protective materials which also possess antimicrobial properties, enhancing food preservation. For instance, films made from carboxymethyl cellulose (CMC) modified with fungal melanin have shown promising results in terms of mechanical strength and antimicrobial activity, making them ideal for food packaging (Lopusiewicz et al., 2021).
2. **Medical uses:** Mushroom mycelium, the vegetative part of fungi, can be processed into bioplastics that exhibit remarkable mechanical properties. Research has demonstrated that mycelium composites can be engineered to create materials with high tensile strength and elasticity, making them suitable for medical applications such as scaffolds for tissue engineering. The biocompatibility of these materials is crucial, as they can support cell growth and tissue regeneration, which is essential for developing effective medical devices (Li et al., 2017).
3. **3D Printing:** In the field of 3D printing, mushroom-derived polymers are being explored as a renewable feedstock for creating eco-friendly prototypes and functional products. Their adaptability allows for precise engineering of materials with specific mechanical and structural properties. The ability to 3D prints, these materials allow for the creation of complex structures that can mimic the natural architecture of biological tissues, enhancing their functionality in medical applications (Kajtez et al., 2022).

Renewable fibers from mushrooms and their application:

Fibers derived from mushrooms, particularly fungal mycelium, represent a new innovation in sustainable material science. These renewable fibers are not only environmentally friendly but also exhibit extraordinary self-healing properties. When cut, torn, or damaged, they can restore themselves simply by being exposed to water. This ability is rooted in the unique structural proteins and chemical composition of mycelium, which enable it to reorganize and repair under the right conditions (Muiruri et al., 2023).

1. **Wearable technology:** In the field of wearable technology, self-healing mushroom fibers offer the potential to create more durable, long-lasting clothing and accessories. Garments made from these fibers could repair small tears or abrasions without the need for stitching, reducing textile waste and extending the life of clothing.
2. **Industrial uses:** In industrial applications, these fibers could be used in equipment, safety gear, and other materials exposed to harsh conditions. Their ability to self-repair reduces maintenance costs and downtime, improving efficiency in fields such as construction, manufacturing, and transportation.

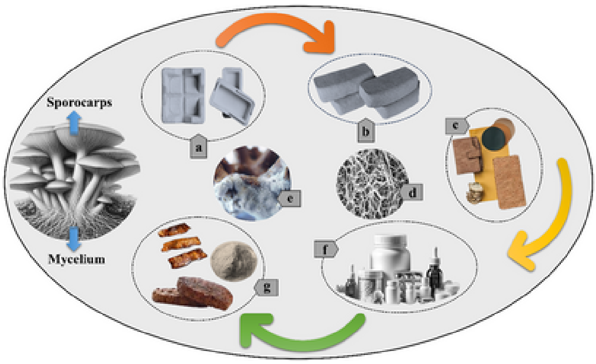

Fig. 1. Sustainable materials and bioproducts from mushrooms, a). mycelium-based packaging material; b). mycelium composites for construction; c). mycelium-based vegan leather for textile industries; d). fungal mycelium for medical uses; e). mycelium biodegradable wooden scaffold; f). mycelium-based products in pharmaceutical industries; g). use of edible fungal mycelium in functional foods

Agro-waste utilization: Mushrooms role in recycling and sustainability

Mushrooms offer a promising pathway for advancing sustainable practices through the utilization of agro-waste materials in mushroom cultivation for functional foods (Aditya et al., 2024a). By recycling agricultural residues such as straw, sawdust and coffee grounds, this approach not only addresses waste management issues but also produces valuable bioproducts (Aditya et al., 2024b). The potential utilization of these agro-wastes varies across different species of oyster mushrooms, with materials like rice straw and wheat bran being particularly effective for *Pleurotus spp.* cultivation (Aditya et al., 2024c), while sawdust and cottonseed hulls are better suited for species like *Hypsizygus ulmarius* (Aditya et al., 2022). These species benefit from the ability of mycelium to break down complex organic materials, leading to efficient nutrient recycling.

Such mycelium-based strategies highlight the role of agro-waste in supporting both environmental sustainability and the growth of mushroom industries, contributing to a more circular bioeconomy.

Circular economy and market potential

The integration of mushrooms, particularly mycelium, into the circular economy model shows considerable promise, particularly in waste reduction and sustainability. Mycelium-based materials are growing in popularity as viable, eco-friendly alternatives to conventional products such as plastics, leathers, and construction materials. These materials contribute to reducing waste by transforming agricultural residues, such as straw and sawdust, into valuable bioproducts, thereby promoting resource efficiency. For instance, mycelium composites used in construction and packaging can be biodegraded at the end of their life cycle, which significantly reduces environmental pollution compared to their synthetic counterparts. As the demand for more sustainable solutions rises, mycelium-based products present a rapidly expanding market with significant potential for growth. In the fashion industry, mycelium is emerging as a substitute for leather, providing a cruelty-free and environmentally conscious option. Furthermore, the versatility of mycelium, coupled with its low-energy production processes, offers significant cost-saving potential compared to traditional materials. However, scaling production to meet large-scale demands and reducing costs to compete with conventional materials remain key challenges. Ongoing research efforts aim to enhance the efficiency of these processes, broaden the range of applications, and ultimately position mycelium as a cornerstone of a sustainable, circular economy. This emerging field aligns with global sustainability goals and could play a pivotal role in transforming various industries into more sustainable, resource-efficient systems.

Challenges and future prospects

Mushroom-based sustainable materials hold immense potential but face significant challenges. Scaling up production to meet industrial demands is complex and resource-intensive, requiring controlled environments and substantial infrastructure. These materials are often more expensive than traditional alternatives like plastics or leather, making it difficult to compete in cost-sensitive markets. Public awareness is another hurdle, as limited knowledge about the benefits and capabilities of mushroom-based products often leads to skepticism and slower adoption rates. Despite these challenges, the future of mushroom-based materials is promising. Research is focused on improving production efficiency through advances in biotechnology and automation, which could reduce costs and enhance scalability. Beyond current uses in packaging, textiles and construction, emerging applications in electronics, medicine and renewable energy systems are expanding their potential. Their alignment with global sustainability goals makes them an attractive option for reducing pollution and fostering a circular economy. Collaboration between researchers, industries and policymakers, along with supportive incentives and regulations, can further accelerate their adoption, positioning mushrooms as a cornerstone of sustainable industries.

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