Fungal Biotec 4(1): 56–67 (2024) ISSN 2774-0323

www.fungalbiotec.org

**Article**

**Doi 10.5943/FunBiotec/4/1/4**

# Diverse use of mushroom mycelium-based as biomaterial products: A mini review

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Khyaju S, Luangharn T. 2024 – Diverse use of mushroom mycelium-based as biomaterial products: A mini review. Fungal Biotec 4(1), 56–67, Doi 10.5943/FunBiotec/4/1/4

## Abstract

Maximum use of non-renewable natural resources is proven to be unsustainable. Extensive research on mushroom mycelium has revealed its potential and applications in daily products. The mushroom mycelium-based biomaterials concept has been used to produce diverse products as an alternative to plastic products. Agriculture waste products, often considered effluents, are effectively repurposed as primary substrates for producing biomaterials. This approach contributes to the promotion of a closed-loop or circular economy. Numerous commercial companies have integrated mushroom mycelium-based biomaterials that adhere to international standards into their products. Mycelium-based materials have applications in various sectors, including packaging, architectural designs, construction, thermal and acoustic insulation, and textiles, specifically synthetic leather. Several prior studies have established that these products demonstrate biodegradability with a lack of residual impact on the environment. This article presents a diverse use of mushroom mycelium to develop different eco-friendly products.

**Keywords** – biotechnology – circular economy – mycelium-based biomaterials – sustainable development

## Introduction

The world population is increasing rapidly, with a current population of 7.7 billion in 2019 from 6.8 billion in 2009 and an estimated 9.7 billion by 2050 (Maraveas 2020). According to United Nations projects (2018), it is anticipated that by the year 2050, approximately 68% of the global population will reside in urban areas. Annual waste generation is anticipated to escalate to 2.2 billion tons by 2025 and reach an imposing 3.40 billion tons by 2050, which implies that annual waste will increase to 2.2 billion tons by 2025 and a staggering 3.40 billion tons by 2050 (Chattopadhyay et al. 2008, Hoornweg & Bhada-Tat 2012, Alemu et al. 2022). According to the escalating waste landscape, synthetic plastics, known as non-biodegradable, have emerged as a significant source of environmental pollution (Holt et al. 2012, Lin et al. 2017). These plastic products are predominantly sourced from finite natural resources, posing sustainability challenges and obstructing the shift towards a circular economy. The manufacturing processes of extruded polystyrene and expanded polyethylene foams are sourced from petroleum-based origins, which involve significant energy consumption. So, the limited and non-renewable petroleum sources direct the world towards crises. There are substantial risks to human health, underscoring the pressing requirement for sustainable waste management solutions (Lopez Nava et al. 2016).

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Submitted 16 Febuary 2024, Accepted 30 April 2024, Published 17 May 2024

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The rapidly growing population has increased the demand for food, leading to the generation of elevated agricultural by-products (Muchovej & Pacovsky 1997). Global agricultural waste is estimated to increase to 2.2 billion tons annually by 2025 (Mulat et al. 2019). The by-product of one crop holds the potential to become a valuable asset for another industry, facilitating the creation of sought-after products. Using agricultural waste as construction material promises to substantially impact the release of greenhouse gas emissions into the atmosphere (Abhijith et al. 2018). Utilizing biomaterials derived from mycelium and organic substrates exhibits favourable attributes for industrial applications. This implementation could revolutionize the linear economic paradigm, altering the current production and disposal model towards a circular economy. Mycelium-based biomaterials present an eco-friendly substitute for conventional materials, promote sustainability, and have the potential to biodegrade (Abhijith et al. 2018).

Mycelium-based biomaterials are safe for users. An alternative product, utilizing mushroom mycelium, has emerged through advancements in science and research. Biomaterials derived from renewable mushroom mycelium offer a multitude of advantages, including energy-efficient production, cost-effectiveness, complete biodegradability, recyclability, potential for carbon dioxide sequestration, sustainable sourcing, lightweight characteristics, low density, robust strength, non-toxic properties, and remarkable suitability for the packaging and construction industries (Jiang et al. 2017, Abhijith et al. 2018, Islam et al. 2018, Fairus et al. 2022). Recently, the packaging industry has experienced a surge in market demand. Attias et al. (2019) reported that some primary manufactured at an industrial scale by three leading companies: Ecovative Design LLC (www.ecovativedesign.com), Mycoworks Inc. (www.mycoworks.com), and Mogu (https://www.mogu.bio/). Jones et al. (2020) reported that the raw material cost of mycelium composites was assessed, demonstrating a production cost range. The cost is notably lower than the wholesale price of polystyrene, such as polystyrene (2.1–2.3 $\$US.kg^{-1}$), polyurethane (8.2–10.4 $\$US.kg^{-1}$), phenolic formaldehyde resin (1.7–1.9 $\$US.kg^{-1}$), foams and plywood (0.5–1.1 $\$US.kg^{-1}$), softwood (0.7–1.4 $\$US.kg^{-1}$), and hardwood (3–11 $\$US.kg^{-1}$) products.

## Mycelium as a binding agent

Mycelium is a vegetative part of filamentous fungi composed of hyphae, which act as unit-binding agents among hyphae and between hyphae and substrates. It is a bonding agent or natural binder for bio-composite materials (Jiang et al. 2016, Abhijith et al. 2018). The mycelium binds with the fibrous inner core and the outer surface of the organic substrates to form a composite, which forms a compact layer termed fungal skin (Appels et al. 2019, Elsacker et al. 2020, Atiwesh et al. 2021). This distinctive hypha property is observed before transferring the mycelium-substrate mixture into the mould during bio-composite preparation. Based on the structure of mushroom mycelium, there are categorized into monomitic, dimitic or trimitic hyphal systems comprised of generative, binding, and skeletal hyphae, which are distinguished by variations in cell wall thickness, internal structure, and branching characteristics (Jones et al. 2020). Numerous contemporary studies underscore the significance of wood-decaying mushrooms, primarily *Ganoderma*, *Pleurotus*, and *Trametes*, as essential components in the advancement of mushroom mycelium-based biomaterials (Aiduang et al. 2022b). Mycelium works as a stabilizing compound for the fibres of the agricultural substrate (Almpani-Lekka et al. 2021). However, to achieve significant or dense mycelial growth with higher mechanical strength on substrates, mushrooms characterized by a trimitic hyphal system are preferred over monomitic or dimitic (Porter et al. 2023). Mycelium density, mycelium structure, and growth rate are important criteria for mushroom species selection for biomaterial preparation (Alemu et al. 2022). In terms of tensile strength performance, biomaterials derived from trimitic fungal species exhibit superior flexural strength (Butu et al. 2020, Manan et al. 2021, Aiduang et al. 2022b). The basic method of mushroom mycelium-based biomaterials is illustrated in Fig. 1.

**Fig. 1 –** Overview of the preparation of mushroom mycelium-based biomaterials.

The utilization of mushroom mycelium has expanded to a commercial scale across various industries (Dessi-Olive 2022). Mushroom mycelium-based biomaterial products have been successfully applied in several products, such as packaging, architectural and design work, building materials, thermal insulation materials, textiles, and leather (Joshi et al. 2020) (Fig. 2). Mycelium-based biomaterials have been a miracle for the new era suffering from non-degradable and non-sustainable products. Mushroom mycelium-based biomaterials are non-toxic and safe, offering a sustainable alternative to environmentally harmful, synthetic, and non-renewable plastics (Raut et al. 2021). The demand for mushroom mycelium-based biomaterials, along with their research and invention, is rising alarmingly. So, it is necessary to compile the recent updates on applications of mushroom mycelium-based biomaterials. This review article mainly comprises diverse uses of mycelium-based bio-composites based on recently published articles focused on the following main five areas.

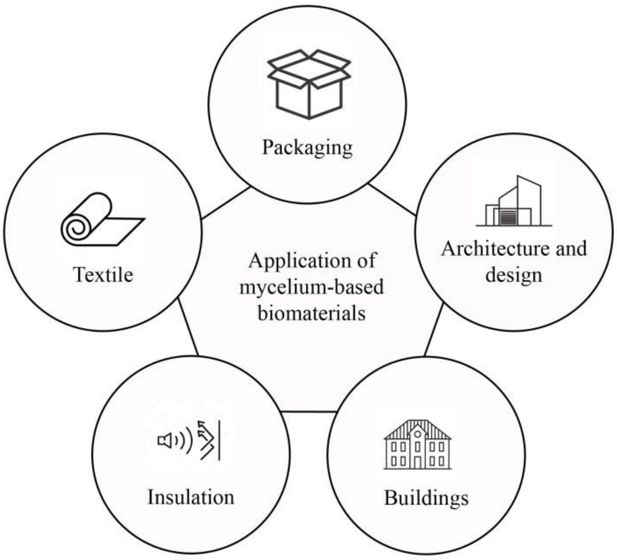

**Fig. 2 –** Application of mushroom mycelium-based biomaterials.

### Applications of mushroom mycelium-based for packaging product

The utilization of mushroom mycelium in packaging materials is a significant step toward sustainable practices, offering a biodegradable alternative to traditional plastics (Abhijith et al.

2018) (Fig. 3). Mushroom mycelium-based packaging addresses environmental concerns, with its rapid growth, natural adhesiveness, and biodegradable properties providing a compelling solution to conventional packaging waste issues (Iordache et al. 2018, Kim & Ruedy 2019). Research explores the potential of mycelium-based packaging in creating biocomposite materials as a viable alternative to traditional packaging (Abhijith et al. 2018, Vandelook et al. 2021). Polystyrene or Styrofoam is one of the major components in petroleum-based synthetic packaging products which pile up as pollutants in the environment (Abhijith et al. 2018). Most of the physical and mechanical properties of mushroom mycelium-based biomaterials showed similarity with polyimide and polystyrene foams (Aiduang et al. 2022b). With comparable mechanical strength to synthetic materials, mycelium-based packaging decomposes naturally, reducing non-biodegradable waste and aligning with consumer and corporate sustainability goals.

Sustainability packaging products have been in demand in the current context relating to environmental issues. Abhijith et al. (2017) reported that one-third of consumers favour environmentally labelled packaging. Biomaterials decompose faster through mushroom mycelium than plastic products. Mushroom mycelium-based biomaterials prepared from *Trametes versicolor* grown on hardwood chips and hemp on composting decomposed up to 70% after four months and were completely biodegradable (Zimele et al. 2020, Aiduang et al. 2022a). Plastic packaging has an extended degradation period, with plastic grocery bags taking 10–20 years, plastic sandwich bags requiring up to 1000 years, plastic straws (100–500 years), plastic bottles (450 years), disposable diapers (450 years), plastic coffee pods (150–500 years), and styrofoam cups (50 years) (Asore 2021). Mushroom mycelium-based packaging products were guaranteed 100% biodegradable and renewable materials to reduce waste (Asore 2021).

Major corporations such as Dell, IKEA, and Ecovative Design have already integrated mushroom mycelium-based biomaterials into their products (Iordache et al. 2018). Specifically, Ecovative Design has demonstrated the EcoCradle$^{TM}$, a line of mushroom mycelium-based packaging products that serve as a sustainable substitute for expanded polystyrene packaging (Holt et al. 2012, Vandelook et al. 2021). Dell Company has a larger plan to incorporate mushroom mycelium products as packaging for sustainable shipping purposes (Abhijith et al. 2018). Additionally, Rajendran (2022) reported that Ford Motor Company has decided to include mycelium-based foam in automotive parts. Mycelium Solutions Company is actively producing mycelium-based packaging materials (Iordache et al. 2018). Consequently, mushroom mycelium-based packaging materials are emerging as the superior alternative in various industries.

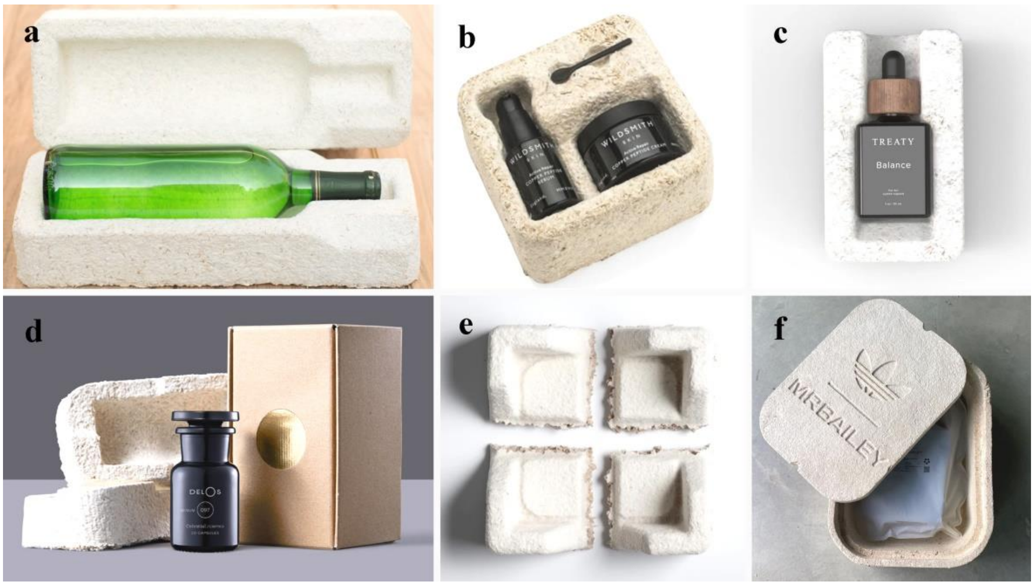

**Fig. 3 –** Mushroom mycelium-based biomaterial packaging products. a–d Cushioning packaging. e Breakaway corners. f Shoebox. References: a, c, e Ecovative (2024), b Vandelook et al. (2021), d Hemptrain (2024), f MrBailey & Adidas (2024).

### Applications of mushroom mycelium-based for architectural works and design

The non-degradable plastic products used in architecture and design have resulted in pollution in the environment (Oral et al. 2022). Almpani-Lekka et al. (2021) reported the potential use of fungal biomaterials in architectural works and design for the last ten years (Fig. 4). New techniques like laser cutting and hot and cold compression are used to get the desired shapes and structures of materials. Fibrous woven scaffolds are useful for growing large-scale mycelium structures (Ozlu & Nicholas 2021). The development of myco-material applications in architectural works and designs has been extensively used, and some of them are briefly presented here. Subsequently, numerous experiments have been undertaken to explore diverse architectural designs in this innovative field.

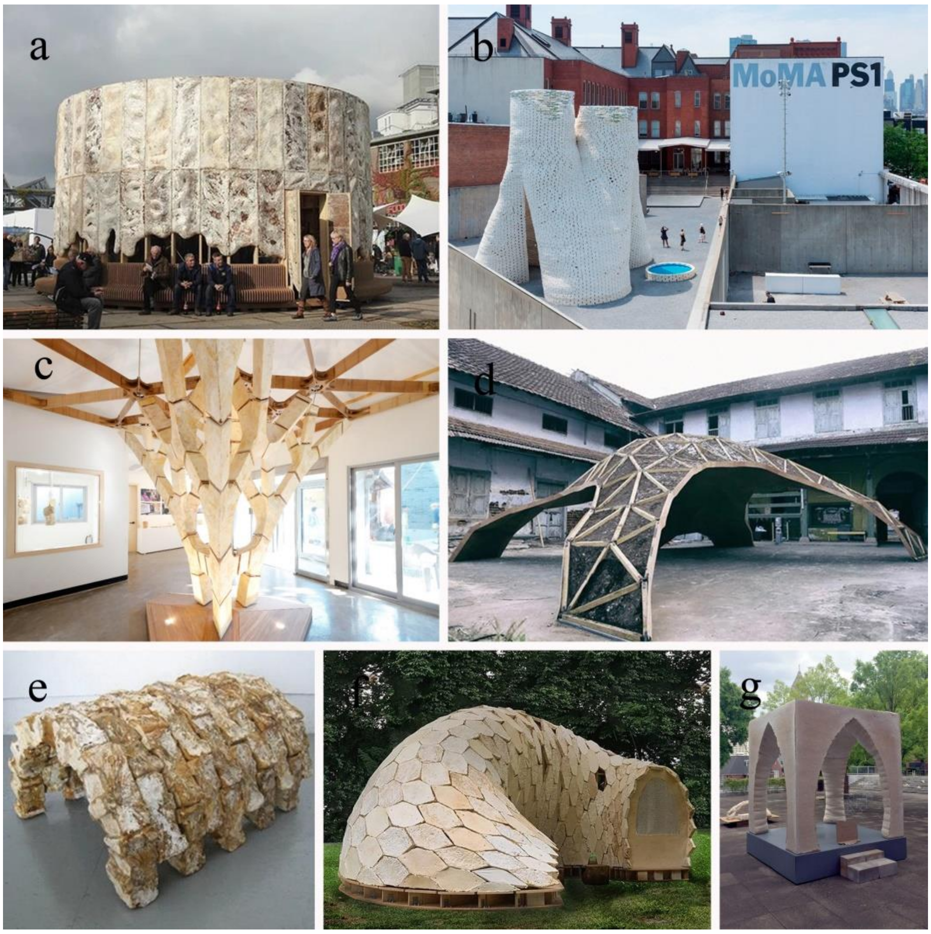

**Fig 4** Architectural designs using mycelium-based materials. a Growing Pavilion. b Hy-fi tower. c The Mycotree Pavilion. d Shell Mycelium. e Mycotectural Alpha. f My-co space. g EI Monolito. References: a, c–g Almpani-Lekka et al. (2021), b Modanloo et al. (2021).

Various pioneering projects highlight the versatility of mycelium in architecture. For example, the Company New Heroes constructed the Growing Pavilion, which utilized biomaterial coatings to enhance water resistance (Almpani-Lekka et al. 2021). David Benjamin employed approximately 10,000 mycelium blocks to create the Hy-Fi pavilion (Almpani-Lekka et al. 2021). Block Research Group designed the MycoTree Pavilion, focusing on interior installations. The Shell Mycelium, designed by Studio Beetles 3.3 and Yassin Arredia Design, allowed on-site cultivation of the mycelium-substrate mixture (Almpani-Lekka et al. 2021). Phil Ross introduced Mycotectural Alpha, marking the inaugural architectural design showcased at Kunsthalle Dusseldorf (Modanloo et al. 2021). In Frankfurt, Germany, the Myco space 2021 by MT-CO-X was a collaborative project with dimensions of 5.2 × 6.0 × 3.0 $m^3$ (Almpani-Lekka et al. 2021). The El Monolito Micelio, designed by the Georgia Institute of Technology School of Architecture, featured vault-formed monolithic castings using 800 kg of mycelium-substrate composite mixture (Almpani-Lekka et al. 2021).

Moreover, the utilization of myco-materials in 3D printing techniques has emerged as an innovative and attention-grabbing development (Goidea et al. 2020, Soh et al. 2020, Dessi-Olive 2022). Bio-welding or myco-welding has gained popularity as a method for design (Dessi-Olive 2022). Mushroom mycelium-based biomaterials exhibit plasticity, enabling their application in design and structural uses. The autonomous binding characteristic of mycelium allows for regrowth upon breakage, and these materials can be reinforced further with the addition of wood and metal connectors.

## Applications of mushroom mycelium-based for building materials

There is a growing demand for construction materials that are sustainable, environmentally friendly, and cost-effective. The average lifespan of buildings has decreased, with only 34 years in China and 25 years in Japan (Liu et al. 2014, Wuyts et al. 2019, Dessi-Olive 2022). This trend contributes to an increased volume of waste in landfills, posing challenges for waste management. Mushroom mycelium-based biomaterials have been applied to produce building components such as bricks, blocks, and panels (Fig. 5). The mycelium-substrate mix is grown in bags and transferred into desired moulds to allow mycelium growth.

The incorporation of agricultural byproducts in the production process enhances the cost-effectiveness of the final product, making it suitable for widespread use. The application of mycelium and agricultural waste in creating low-energy construction materials has garnered attention from researchers and investors (Madurwar et al. 2013). By combining inexpensive agricultural waste with mycelium, various products like bricks, blocks, panels, and essential construction components can be manufactured, reducing overall production requirements (Holt et al. 2012, Jones et al. 2017).

**Fig. 5** – Mushroom mycelium pre-composite blocks prepared with different combinations of mushroom strains and substrates.

The potential for creating interlocking blocks has expanded the application of biomaterials in construction, showcasing water and fire resistance. Sharma & Sumbria (2022) report that mycelium bricks display lower brittleness and higher ductile properties than materials without mycelium. Moreover, these biomaterials conform to international standards for thermal and acoustic insulation, dry density, and other construction material requirements (Saez et al. 2021). In contrast, mycelium-based composites pose specific constraints for constructing larger structures, necessitating scaffolds or comprehensive reinforcement systems (Dessi-Olive 2019, Ozdemir et al. 2022). Insufficient data is available regarding the impact of reinforcement with mushroom mycelium-based biomaterials. Notably, these composites exhibit hydrophilic properties compared to synthetic materials used on external building surfaces, presenting a potential recommendation challenge (Tsao 2020). Additional research is essential to address the lack of tension and bending resistance in mycelium-based composites.

### Applications of mushroom mycelium-based for insulating materials

The shift towards using mushroom mycelium for insulation purposes represents a notable advancement in the construction and insulation industries, offering an eco-friendly alternative to traditional methods. Conventional insulation, often reliant on polystyrene foams, contributes to environmental pollution upon disposal and poses health risks due to its synthetic or petroleum-based nature, including carcinogenic properties (Sulong et al. 2019, Tsao 2020). The innovation of incorporating mushroom mycelium with lignocellulosic substrates proves effective in acoustic absorption. Pelletier et al. (2013) reported that mycelium-based boards show promise as bio-based alternatives to synthetic foams for sound insulation. The inherent porous structure of mushroom mycelium-based biomaterials enhances their sound absorption properties, making them well-suited for applications in sound control.

The noise absorption capability of mushroom mycelium-based biomaterial panels is substrate-dependent (Meyer et al. 2020, Yang et al. 2021). In a compact form, mycelium disrupts the path of sound waves, diminishing their amplitude and converting them into heat energy (Peters 2013). It effectively absorbs low frequencies (below 1500 Hz), making it suitable for noise absorption applications, such as replacing ceiling tiles to mitigate noise pollution (Manan et al. 2021, Gou et al. 2021). This product serves as an environmentally friendly alternative to synthetic and non-degradable insulation materials (Vandelook et al. 2021).

Mycelium-based composites demonstrate satisfactory characteristics for thermal insulation (Elsacker et al. 2019, Elsacker et al. 2021). Jones et al. (2020) stated that the lower thermal conductivities indicate superior insulation materials. Mushroom mycelium-based biomaterials exhibit superior fire resistance compared to conventional building materials relying on polystyrene insulation and particle boards (Boyer 2014, Silverman et al. 2020, Tsao 2020, Oral et al. 2022). According to Tsao (2020) reported that the thermal conductivity of mycelium-based foams ranges between 0.04–0.13 ($W.m^{-1}.K^{-1}$), slightly higher than conventional foams ranging between 0.03–0.04 ($W.m^{-1}.K^{-1}$). This development opens new possibilities for an industry focused on enhancing the fire safety of buildings.

In regions with temperate climates, effective wall insulation is crucial for maintaining comfortable temperatures indoors. The use of mushroom mycelium-based biomaterials in wall insulation can successfully preserve insulating properties. Ecovative Design, for instance, has developed a fire-retardant board called Greensulate, which has gained popularity as an effective insulating product (Casini 2016, Abhijith et al. 2018, Rajendran 2022).

### Applications of mushroom mycelium-based for textile as a leather product

Mushroom mycelium-derived leather stands out as an environmentally safe, green, and sustainable alternative compared to animal-sourced and synthetic products (Vandelook et al. 2021, Raman et al. 2022). In contrast, conventional leather production involves using numerous toxins and chemicals, including harmful substances (Silva 2021).

Pure fungal materials for leather production can be obtained through completely degrading substrates or fungal mats from liquid or solid surfaces (Cartabia et al. 2021). Mushroom mycelium-based leather is considered safe for use due to its beneficial properties for human skin. German company ZVNDER conducted successful tests, demonstrating the positive effects of mycelium leather on an athlete's foot, with mycelium-based shoes offering advantages such as improved air circulation to prevent unpleasant odours (Gandia et al. 2021).

Furthermore, the Bolt Threads Company, renowned for producing the mycelium-based product Mylo, positions itself as an alternative to traditional leather (Iordache et al. 2018). Mushroom mycelium-based leather is lighter than traditional animal-based leather, providing advantages for both industries and consumers. This lightweight property makes it suitable for a diverse range of applications. The fashion industry has embraced mushroom mycelium-based biomaterials in producing sustainable alternatives for clothing, bags, and shoes, leading to the creation of luxury fashion items that contribute to a modern and sensual aesthetic.

Vasquez and Vega (2019) reported the preparation of myco-accessories, such as necklaces, crowns, and bracelets, using a thin layer of mycelium with a lamination technique, showcasing the artistic and decorative potential of mycelium-based materials. Moreover, mycelium-based materials have demonstrated utility in supporting electronic circuit boards (Vasquez et al. 2019, Vandelook et al. 2021), indicating their potential applications beyond fashion and accessories.

Conventional leather production involves the slaughter of animals, contributing to ethical concerns raised by animal rights activists (Gupta & Dave 2021, Silva 2021, Raman et al. 2022) Mushroom mycelium-based leather provides a cruelty-free alternative, eliminating the need for animal hides. One advantage of mushroom mycelium-based leather is its rapid growth, allowing it to be ready in a short period, contrasting with animal-derived leather, which requires years.

Consumers increasingly prioritize environmentally safe leather and fabric products. Mushroom mycelium-based leather offers a low production cost without the need for chemical processing. Certain plasticizers, such as glycerol, polyethylene glycol, PEG400, mono/di/oligosaccharides, lipid, and lipid derivatives, are employed to enhance desirable characteristics, reducing brittleness and hardness while increasing elongation and ductility (Janjarasskul & Krochta 2010, Raman et al. 2022). Although mushroom mycelium-based leather has not fully matched the commercial success of traditional animal-sourced and synthetic leather, ongoing extensive research holds the promise of discovering better options for sustainable products. Companies like MycoWorks and MOGU Inc. have successfully utilized mycelium to develop synthetic leather (Rajendran 2022).

## Discussion

The global emphasis on sustainability has prompted a shift towards incorporating circular economy principles that leverage renewable natural resources in industrial practices. The production process requires eco-friendly, green, and cost-effective options. Mycelium-substrate composite is being successfully applied in the production of packaging, architectural designs, building, thermal and sound insulation, and textiles (leather). These products exhibit qualities such as being lightweight, easily manageable, safe for both humans and wildlife, readily decomposable, and aesthetically appealing. Mushroom mycelium-based biomaterial products represent a significant advancement toward sustainable and eco-conscious solutions across various industries, and they stand poised to address pressing environmental challenges and contribute to the realization of circular economy principles. Embracing the potential of mushroom mycelium-based biomaterials heralds a promising future where innovation aligns with ecological stewardship for the benefit of present and future generations.

## Acknowledgements

Sabin Khyaju thanks Thesis support grant from Mae Fah Luang University (reference no. GR-ST-PS-65-22) and Mushroom Research Foundation, Chiang Rai, Thailand. Thatsanee Luangharn would like to thank the National Research Council of Thailand (NRCT) “Total fungal diversity in a given forest area with implications towards species numbers, chemical diversity and biotechnology” (grant no. N42A650547), and the Fundamental Fund supported by the National Science, Research and Innovation Fund “Taxonomy, phylogeny, screening of biologically active secondary metabolite and cultivation of *Ganoderma* species” (grant no. 662A16005, 672A16004).

## Accessibility of data

All data presented or analyzed during this study are included within the article.

**Conflicts of interest:** The authors declare no conflict of interest.

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