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Article

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A global checklist of mushrooms (Basidiomycota) in biomaterials and the challenges and opportunities of mycelium-based biomaterials

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Abstract

Mushroom mycelium-based biomaterials (MMBs) are innovative, environment-friendly, biodegradable, and sustainable alternatives to plastic- and foam-based products. MMBs are popular due to their biodegradability, low carbon footprint, and alignment with the principles of the circular economy. MMBs are developed using the mycelium of suitable mushroom species and lignocellulosic substrates, derived from agricultural and forest byproducts. Research on several mushroom species is increasing, and the choice of species plays a pivotal role in determining the mechanical and overall characteristics of the end products. This review is the first compiled report of all mushroom species within Basidiomycota utilized in MMBs production. The mushroom genera used in its development have also been presented according to hyphal system type. This paper is based on all the relevant published and available articles till 2024. Additionally, it highlights key challenges in developing MMBs and explores potential solutions.

Keywords – fungal application – hyphal system – mushroom species – renewable – sustainable material

Introduction

Mushrooms are the fruiting bodies of fungi that grow above ground or on a substrate, primarily belonging to the phylum Basidiomycota. They include gilled fungi, puffballs, bracket fungi, coral fungi, jelly fungi, and crust fungi (Rathore et al. 2019). Since ancient times, mushrooms have been widely used in food, medicine, and the extraction of secondary compounds (Rathore et al. 2019). They are an important source of bioactive and medicinal compounds, such as terpenoids, polysaccharides, proteins, and vitamins, and are known for their antioxidant, antimicrobial, anticancer, antitumor, and immunomodulatory properties. Among several applications of mushrooms, mushroom mycelium-based biomaterials (MMBs) are a novel class of sustainable, eco-friendly, and biodegradable materials. As a result, research and development on MMBs is growing worldwide, with major efforts in Asia, Europe, and North America (Fig. 1).

Mycelium, the vegetative structure of filamentous fungi, acts as a unit-binding agent, connecting hyphae and substrates (Jiang et al. 2016, Abhijith et al. 2018). It grows on lignocellulosic

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substrates, forming two- or three-dimensional networks (Crowther et al. 2014). The MMBs offer numerous benefits, such as energy-efficient production, cost-effectiveness, complete biodegradability, potential for carbon dioxide sequestration, sustainable sourcing, lightweight nature, low density, high strength, and non-toxic properties (Jiang et al. 2017, Abhijith et al. 2018, Islam et al. 2018, Fairus et al. 2022). These features make MMBs an excellent eco-friendly alternative to conventional materials, supporting sustainability, effective biodegradability, and environmental protection (Abhijith et al. 2018, Hyde et al. 2024a).

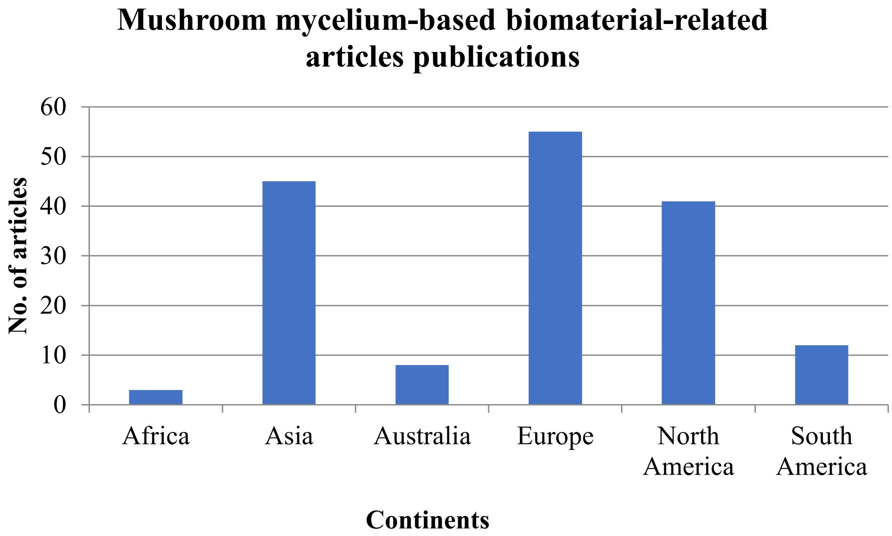

Fig. 1 – Mushroom mycelium-based biomaterials-related articles published up to 2024 from different continents. The data is based on findings on online platforms (Google Scholar, PubMed, ScienceDirect, Wiley Online Library, Semantic Scholar) and using keywords, such as mycelium-based biomaterial, mycelium-based composite, mycelium-based leather, and pure mycelium materials.

A key factor in selecting mushroom candidates for MMBs preparation is the distinctive hyphal properties (Manan et al. 2021, Aiduang et al. 2022b, Porter et al. 2023). Mushrooms are categorized into monomitic, dimitic, or trimitic hyphal systems based on the presence and composition of generative, skeletal, and ligative or binding hyphae (Jones et al. 2020). They differ in cell wall thickness, internal structure, and branching patterns (Jones et al. 2020). For robust mycelial growth with enhanced mechanical strength, mushrooms with a trimitic hyphal system are preferred over monomitic or dimitic systems (Butu et al. 2020, Manan et al. 2021, Aiduang et al. 2022b, Porter et al. 2023).

The MMBs have several applications, including packaging, construction, thermal and acoustic insulation, architectural design, and textiles (Joshi et al. 2020, Khyaju & Luangharn 2024). These sustainable innovations have attracted people and companies and hold the potential to be incorporated into human daily life (Elsacker et al. 2020). The use of mycelium has expanded from an experimental laboratory to large-scale commercial applications, including companies such as Ecovative Design, Mycoworks, and Mogu, which are producing MMBs (Attias et al. 2019, Dessi-Olive 2022). Additionally, the increasing number of patent applications and approvals signifies the industrial significance of MMBs.

Basidiomycota constitutes four subphyla, 20 classes, 77 orders, 297 families, 2,134 genera, and approximately 41,270 recognized species worldwide (He et al. 2019, 2024, Hyde et al. 2024b). Hibbett (2007) estimated that there were 37,717 Agaricomycetes species. However, only a countable number of mushroom species, such as *Ganoderma*, *Lentinus*, *Pleurotus*, and *Trametes*, have been studied for MMB production, leaving many species unexplored (Fig. 2) Research on mushroom species to develop MMBs with superior material properties is increasing worldwide. Recently, genetically modified mushroom species (GMO) have broadened the technological capabilities in biomaterial development (Madusanka et al. 2024). The most popular genome editing technique, CRISPR/Cas9, has been successfully applied to several mushroom species, including *Agaricus bisporus*, *Ganoderma lucidum*, *Lentinula edodes*, and *Schizophyllum commune* (Jan Vonk et al. 2019, Song et al. 2019, Liu et al. 2020, Choi et al. 2023, Kamiya et al. 2023). Genetic modification by incorporation of a *Saccharomyces cerevisiae* CDA1 chitin deacetylase-encoding gene controlled by glyceraldehyde-3-phosphate dehydrogenase promoter in a *Ganoderma* sp. showed higher β-glucan content (Madusanka et al. 2024). In *Schizophyllum commune*, deletion of the hydrophobin gene sc3 increased the density of pure mycelium, resulting in enhanced mechanical properties compared to its wild-type strain (Appels et al. 2018). However, the knowledge required to utilise the rest of the taxa for MMBs remains underexplored.

Fig. 2 – Mushroom genera (representative) commonly used in mushroom mycelium-based biomaterial development. a *Ganoderma williamsianum*. b *Lentinus squarrosulus*. c *Pleurotus ostreatus*. d *Trametes hirsuta*.

The fragmented information on the research and findings on mushroom species used in MMBs needs to be compiled. The polyphasic approach to identify mushroom species, combining morphology and phylogeny, is crucial before application in MMBs. The undisclosed name of the mushroom species used in MMBs cannot be overlooked and needs to be categorized for consistency and reliability. In addition, pointing out the key limitations and a way out for MMBs research was lacking. These identified knowledge gaps can provide a basis for comprehensive research. In this study, information on mushroom species utilized in MMBs from all available published works up to 2024 has been documented, providing a centralized reference for the field. The details on the hyphal system type, substrates used, and the end products have provided insights into the current scenario and future scope. Besides the critical investigation on the reported limitations or challenges in this sector, this study has provided rational ways to strengthen the research, their development, and commercial production.

Mushroom species in mycelium-based biomaterials

Mushroom mycelium expands through the growth of hyphal apical tips, eventually forming dense mycelial colonies (Islam et al. 2018). These colonies are composed of hyphae, which are fibrous, thread-like structures made of natural polymers such as chitin, beta-glucans, and proteins that provide structural integrity, durability, and functionality (Ruiz-Herrena 1991, Islam et al. 2017). The outer surface of hyphae is rich in beta-glucans, which act as mucilage, along with chitin microfibrils that provide mechanical rigidity and strength (Ruiz-Herrena 1991). Mycelium colonies interconnect randomly through anastomosis, creating a network of hyphae. Saprobic mushrooms use their mycelium networks to degrade lignocellulosic residues into simpler forms of nutrients and bind the substrates together through complex biochemical processes. The mycelium penetrates the substrates via physical pressure and enzymatic secretion, allowing it to access essential nutrients (Rathore et al. 2019).

The development of MMBs has been explored using a limited number of mushroom species, primarily from the orders *Polyporales* (67 species) and *Agaricales* (20 species), and a few from the orders *Hymenochaetales* (6 species), *Auriculariales* (2 species), *Russulales* (2 species), and *Gleophyllales* (1 species) (Fig. 3, Table 1, 3). The differences between the fungal species described and those used in MMBs underscore the need for a more systematic study to explore their immense potential. All the described fungal species might not be suitable for superior-quality MMBs development. To provide a systematic direction for MMBs research, selection criteria for fungal species are crucial. Research on MMBs ranges from preliminary characterization studies to applications in certain sectors such as packaging, construction, architectural designs, and textiles. Based on extensive studies, some scholars have proposed a set of key criteria for selecting fungal species suitable for MMBs production (Sydor et al. 2022, Aiduang et al. 2024). The criteria for selecting suitable fungal candidates can be summarized as follows: vigorous hyphal growth, trimitic or dimitic hyphal systems, classification as white-rot fungi, adaptability to a wide range of substrates and growth conditions, non-sporulating behaviour, saprobic lifestyle, antimicrobial properties, and non-toxicity and non-allergenic.

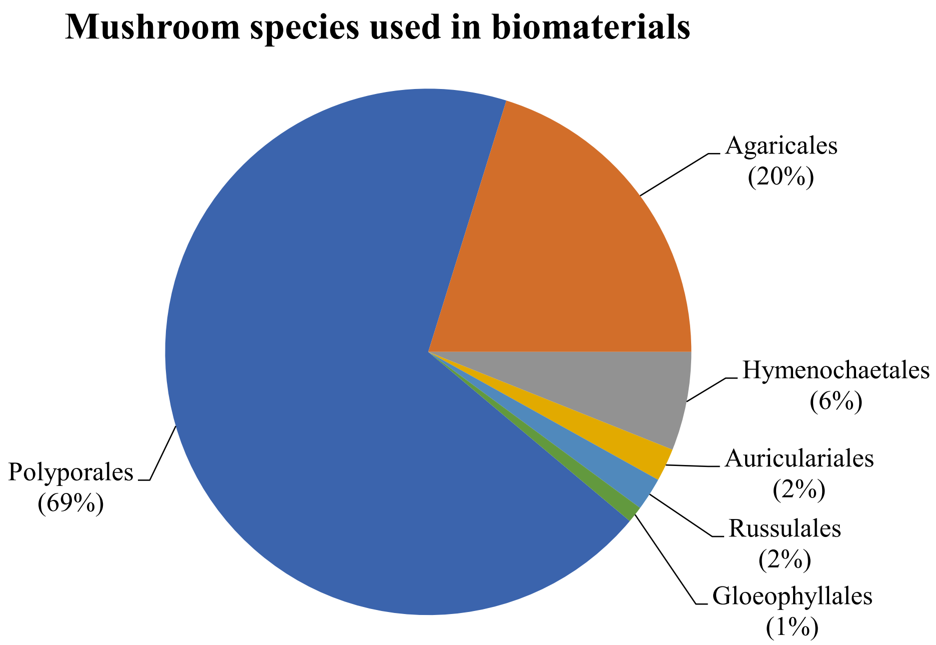

Fig. 3 – Mushroom species belonging to different orders commonly used in the mycelium-based biomaterials applications.

Table 1 Overview of mushroom species examined in experimental studies for mycelium-based biomaterials (MMBs).

Order	Family	Genus	Species
Agaricales	Agaricaceae	*Agaricus*	*A. bisporus, A. bitorquis*
	Lyophyllaceae	*Hypsizygus*	*H. ulmarius*
	Omphalotaceae	*Lentinula*	*L. edodes*
	Physalacriaceae	*Flammulina*	*F. velutipes*
		Oudemansiella	*O. radicata*
	Pleurotaceae	*Pleurotus*	*P. albidus, P. citrinopileatus, P. cornucopiae, P. djamor, P. eryngii, P. ostreatus, P. pulmonarius, P. salmoneostramineus*
	Pluteaceae	*Volvariella*	*V. volvacea*
	Psathyrellaceae	*Coprinopsis*	*C. cinerea*
	Schizophyllaceae	*Schizophyllum*	*S. commune*
	Strophariaceae	*Kuehneromyces*	*K. mutabilis*
		Stropharia	*S. rugosoannulata*
	Tubariaceae	*Cyclocybe*	*C. aegerita*
Auriculariales	Auriculariaceae	*Auricularia*	*A. auricula-judae, A. polytricha*
Gloeophyllales	Gloeophyllaceae	*Gloeophyllum*	*G. sepiarium*
Hymenochaetales	Hymenochaetaceae	*Fomitiporia*	*F. mediterranea*
		Inonotus	*I. obliquus*
		Nothophellinus	*N. andinopatagonicus*
		Phellinus	*P. igniarius*
	Incertae sedis	*Trichaptum*	*T. abietinum*
	Oxyporaceae	*Oxysporus*	*O. latermarginatus*
Polyporales	Cerrenaceae	*Cerrena*	*C. zonata*
	Dacryobolaceae	*Postia*	*P. balsamea*
	Fomitopsidaceae	*Fomitopsis*	*F. iberica, F. pinicola, F.rossea*
		Piptoporus	*P. betulinus*
		Wolfiporia	*W. extensa*
	Grifolaceae	*Grifola*	*G. frondosa*
	Incertae sedis	*Aegerita*	*A. agrocibe*
		Ryvardenia	*R. cretacea*
	Irpicaceae	*Ceriporia*	*C. lacerata*
		Irpex	*I. lacteus*
	Laetiporaceae	*Laetiporus*	*L. sulpureus*
		Phaeolus	*P. schweinitzii*
	Meruliaceae	*Aurantiporus*	*Aurantiporus* sp.
		Irpiciporus	*I. pachyodon*
	Panaceae	*Panus*	*P. conchatus*
	Phanerochaetaceae	*Bjerkandera*	*B. adusta*
		Phanerochaete	*P. chrysosporium*
		Terana	*T. caerulea*
	Podoscyphaceae	*Abortiporus*	*A. biennis*
	Polyporaceae	*Cerioporus*	*C. lacerata*
		Coriolopsis	*C. gallica, C. rigida, C. trogii*
		Daedaleopsis	*D. confragrosa, D. tricolor*
		Earliella	*E. scabrosa*
		Fomes	*F. formentarius*

Table 1 Continued.

Order	Family	*Genus*	*Species*
		Fomitella	*F. fraxinea*
		Funalia	*F. trogii*
		Ganoderma	*G. applantum, G. australe, G. carnosum, G. curtisii, G. fornicatum, G. lingzhi, G. lucidum, G. mexicanum, G. resinaceum, G. sessile, G. steyaertanum, G. williamsianum*
		Hexagonia	*Hexagonia* sp.
		Lentinus	*L. arcularius, L. crinitus, L. polychrous, L. sajor-caju, L. squarrosulus, L. velutinus*
		Lenzites	*L. betulinus*
		Megasporoporia	*M. minor*
		Microporus	*M. affinis*
		Neofavolus	*N. alveolaris*
		Polyporus	*P. arcularius, P. brumalis, P. squamosus*
		Trametes	*T. coccinea, T. gibbosa, T. hirsuta, T. multicolor, T. ochracea, T. orientalis, T. pubescens, T. suaveolens, T. versicolor, T. villosa*
Russulales	Hericiaceae	*Hericium*	*H. erinaceus*
	Stereaceae	*Stereum*	*S. hirsutum*

Note: The taxon name is provided in the same format as the published paper.

Mushroom hyphal systems

Hyphae serve as the fundamental structural units that collectively form mycelium and basidiomata. Mycelium functions as a natural adhesive, binding substrates together and contributing to the structural integrity of mycelium-based biomaterials (MMBs). Mushrooms are classified into three hyphal systems based on their composition: monomitic, dimitic, and trimitic (Fig. 3) (Shin et al. 2025). Monomitic hyphal system consists only of generative hyphae, whereas dimitic hyphal system incorporates generative hyphae with either skeletal or ligative hyphae. In contrast, the trimitic hyphal system contains all three hyphal types, which enhance structural properties. The hyphal system type of mushrooms affects the mechanical and material properties of MMBs (Porter & Naleway 2022). Therefore, selecting suitable mushroom species is a critical factor for producing high-quality biomaterials (Aiduang et al. 2024). The classification of mushroom species used in biomaterial applications is based on their hyphal system (Table 2).

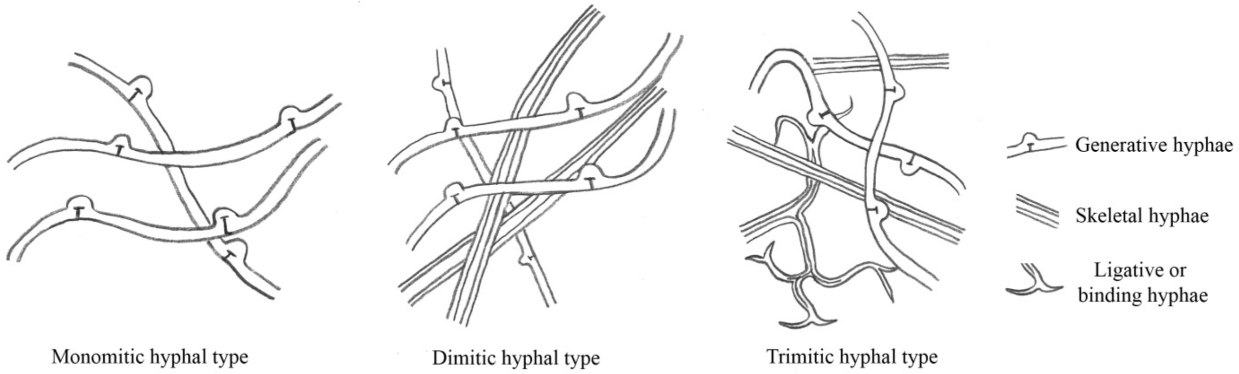

Fig. 3 – A schematic representation of hyphal system types.

Table 2 Classification of mushroom species used in the development of mycelium-based biomaterials based on hyphal system.

Mushroom hyphal systems		
Monomitic	**Dimitic**	**Trimitic**
Agaricus bisporus	*Cerioporus laceratus* (*Polyporus megasporoporus*)	*Coriolopsis gallica*
Agaricus bitorquis	*Cerrena zonata*	*C. rigida* (*Funalia rigida*)
Abortiporus biennis	*Fomitella fraxinea* (*Vanderbylia fraxinea*)	*C. trogii* (*Trametes trogii*)
Aurantiporus sp.	*Fomitiporia mediterranea*	*Daedaleopsis confragosa*
Auricularia auricula-judae	*Fomitopsis iberica* (*F. marianiae*)	*D. tricolor*
A. polytricha (*A. nigricans*)	*F. pinicola*	*Earliella scabrosa*
Bjerkandera adusta	*F. rosea* (*Rhodofomes roseus*)	*Fomes fomentarius*
Ceriporia lacerata (*Irpex laceratus*)	*Ganoderma mexicanum* (*Phellinus nilgheriensis*)	*Funalia trogii* (*Trametes trogii*)
Coprinopsis cinerea	*Grifola frondosa*	*Ganoderma applanatum*
Cyclocybe aegerita	*Irpex lacteus*	*G. australe*
Flammulina velutipes	*Irpiciporus pachyodon*	*G. carnosum*
Hericium erinaceus	*Laetiporus sulphureus*	*G. curtisii*
Hypsizygus ulmarius	*Lentinus arcularius*	*G. fornicatum*
Inonotus obliquus	*L. crinitus*	*G. lingzhi* (*G. sichuanense*)
Kuehneromyces mutabilis	*L. polychrous*	*G. lucidum*
Lentinula edodes	*L. sajor-caju*	*G. resinaceum*
Oudemansiella radicata (*Hymenopellis colensoi*)	*L. squarrosulus*	*G. sessile* (*G. resinaceum*)
Phanerochaete chrysosporium	*L. velutinus*	*G. steyaertanum*
Phaeolus schweinitzii	*Neofavolus alveolaris*	*G. williamsianum*
Pleurotus albidus	*Oxyporus latemarginatus* (*Irpex latemarginatus*)	*Hexagonia* sp.
P. citrinopileatus	*Panus conchatus*	*Lenzites betulinus*
P. cornucopiae	*Phellinus igniarius*	*Microporus affinis*
P. djamor	*Piptoporus betulinus* (*Fomitopsis betulina*)	*Stropharia rugosoannulata*
P. eryngii	*Polyporus arcularius* (*Lentinus arcularius*)	*Trametes coccinea*
P. ostreatus	*P. brumalis* (*L. brumalis*)	*T. gibbosa*
P. pulmonarius	*P. squamosus* (*Cerioporus squamosus*)	*T. hirsuta*
P. salmoneostramineus (*P. djamor*)		*T. multicolor* (*T. ochracea*)
Postia balsamea	Di-trimitic	*T. ochracea*
Ryvardenia cretacea	*Gloeophyllum sepiarium*	*T. orientalis*
Schizophyllum commune	*Megasporoporia minor*	*T. pubescens*
Terana caerulea	*Nothophellinus andinopatagonicus*	*T. suaveolens*
Volvariella volvacea	*Trichaptum abietinum*	*T. versicolor*
Wolfiporia extensa		*T. villosa*
	Psuedodimitic	
	Stereum hirsutum	

Note: The taxon name in parentheses indicates the current name according to Index Fungorum (accessed on 29.03.2025).

Table 3: Basidiomycetes mushroom species, primary substrates, and intended applications of mycelium-based biomaterials (MMBs).

Mushroom species	Main substrates	Intended application	Country	References
Abortiporus biennis, Bjerkandera adusta, Coriolopsis gallica, C. trogii, Daedaleopsis confragosa, D. tricolor, Fomes fomentarius, Fomitiporia mediterranea, Fomitopsis iberica, F. pinicola, Ganoderma carnosum, G. lucidum, Irpex lacteus, Irpiciporus pachyodon, Lenzites betulinus, Neofavolus alveolaris, Stereum hirsutum, Terana caerulea, Trametes hirsuta, T. suaveolens	Malt Extract Agar (MEA), millet slurry	Leather	Italy	Cartabia et al. (2021)
Abortiporus biennis, Bjerkandera adusta, Daedaleopis tricolor, Fomes fomentarius, Irpex lacteus, Lentinus arcularius, Pleurotus ostreatus, Trametes versicolor	Wheat bran, minced wheat straws, coconut husk fibres, broadleaves sawdust	Packaging	Romania	Balaes et al. (2023)
Agaricus bisporus, Flammulina velutipes, Ganoderma lucidum, Kuehneromyces mutabilis, Lentinula edodes, Pleurotus ostreatus, P. ostreatus sajorcaju, P. ostreatus florida	Oak husk, rapeseed cake	Biocomposites	Finland	Tacer-Caba et al. (2020)
Agaricus bisporus, A. bitorquis	Wheat straw	Building insulation materials	Chile	Velasco et al. (2014)
Agaricus bisporus, Fomes fomentarius, Ganoderma applanatum, Trametes versicolor	Bleached softwood kraft fibers, hemp fibers	Mycocel biopolymers	Latvia	Irbe et al. (2021)
Agaricus bisporus, Hericium erinaceus (spent mushroom)	Birch sawdust	Packaging materials	Austria	Zhao et al. (2024)
Agaricus bisporus, Trametes versicolor	Sugarcane molasses	Industrial applications (paper, coatings)	Australia	Jones et al. (2019a)
Aurantiporus sp., *Ganoderma curtisii, G. mexicanum, Lentinus crinitus, Panus conchatus, Pleurotus ostreatus*	Potato Dextrose Agar (PDA)	Mycelium films	Mexico	César et al. (2021a)
Auricularia auricula-judae, Lentinus polychrous, L. squarrosulus, Pleurotus ostreatus	Rice husks, coconut husks, rice straw	Biocomposites	Thailand	Ly & Jitjak (2022)
Auricularia auricula-judae, Pleurotus ostreatus, P. sajor-caju, Schizophyllum commune	Water hyacinth, rice bran	Biocomposites	Thailand	Sakunwongwiriya et al. (2024)
Auricularia polytricha, Ganoderma lucidum, Pleurotus ostreatus	Rubber tree sawdust, diaper core, food waste (coffee, banana, skin, eggshell, sugarcane)	Bio-boards	China	Khoo et al. (2020)

Table 3 Continued.

Mushroom species	Main substrates	Intended application	Country	References
Auricularia polytricha, Ganoderma lucidum, Pleurotus ostreatus	Potato Dextrose Broth (PDB)	Mycelium mats	China	Shao et al. (2024)
Bjerkandera adusta, Elfvingia applanata, Fomitella fraxinea, Fomitopsis pinicola, F. rosea, Ganoderma applanatum, G. lucidum, Microporus affinis, Postia balsamea, Trametes versicolor, T. suaveolens, Wolfiporia extensa	Oak sawdust, rice bran	Leather	South Korea	Raman et al. (2022)
Ceriporia lacerata	Soybean straw	Insulation materials	China	Shao et al. (2016)
Cerrena sp., *Ganoderma* sp., *Pycnoporus* sp.	White wood sawdust, coffee waste, coffee grounds, wheat bran	Biocomposites	Brazil	de Oliveira et al. (2022)
Coprinospsis cinerea, Pleurotus djamor	PDA	Biocomposites	China	Chang et al. (2019)
Coriolopsis rigida, Pycnoporus sanguineus, Trametes villosa	Sawdust of eucalyptus, pine	Biocomposites	Brazil	Catto et al. (2014)
Coriolus brevis, C. hirsuta, C. versicolor, Fomitella fraxinea, Ganoderma lucidum, Polyporus arcularius, P. squamosus, Pycnoporus coccineus, T. fuciformis, Trametes gibbosa, T. orientalis	Sawdust, PDB	Mycelium mats	South Korea	Bae et al. (2021)
Coriolus versicolor, Pleurotus ostreatus	Wood chips, hemp hurd, loose hemp fiber, non-woven hemp mats	Biofoams	Netherlands	Lelivelt et al. (2015)
Coriolus versicolor, P. ostreatus	Hemp herds, woodchips	Insulation materials	Germany	Reibert et al. (2022)
Cyclocybe aegerita, Pleurotus ostreatus, P. pulmonarius, P. salmoneo-stramineus	Woodchips substrates of Eucalyptus, Oak, Pine, Apple, Vine	Design and architecture	Israel	Attias et al. (2017)
Daedaleopsis confragosa, Ganoderma resinaceum, Trametes versicolor	Corn stover, kenaf pith, hemp pith	Biocomposites	USA	Bajwa et al. (2017)
Daedaleopsis tricolor, Fomes fomentarius, Stereum hirsutum, Trametes versicolor	Hemp shives	Biocomposites	Belgium	Verhelst et al. (2024)
Earliella sp., *Hexagonia* sp., *Lentinus* sp., *Pleurotus* sp., *Pycnoporus* sp.	Rubber sawdust, rice straw	Biocomposites	Thailand	Aiduang et al. (2022c)
Flammulina velutipes, Ganoderma applanatum, G. lucidum, Hericium erinaceus, Lentinula edodes, Pleurotus eryngii, Trametes hirsuta	Malt agar, cellulose microcrystals, cellulose microfibrills	Mycelium mats	Russia	Rakitina et al. (2022)
Flammulina velutipes, Lentinula edodes, Lentinus polychrous, Pleurotus ostreatus	Coconut husk, rice husk	Biocomposites	Thailand	Ly & Jitjak (2020)
Fomes fomentarius	Hemp shives, rapeseed straw	Biocomposites	Germany	Pohl et al. (2022)

Table 3 Continued.

Mushroom species	Main substrates	Intended application	Country	References
F. fomentarius	Hemp shives	Insulation materials	Germany	Schmidt et al. (2023)
F. fomentarius	Hemp shives, rapeseed straw, poplar wood chips	Construction materials	Germany	Stelzer et al. (2021)
Fomes fomentarius, Fomitopsis pinicola, Ganoderma lucidum, Irpex lacteus, Pleurotus ostreatus, Schizophyllum commune, Trametes versicolor	Cellulose from softwood kraft pulp	Cellulose fibre foams	USA	Amstislavski et al. (2024)
Fomes fomentarius, Fomitopsis pinicola, Pleurotus eryngii, Trametes versicolor	Malt Extract Broth (MEB), woven fabric	Mycelium mats	Germany	Kniep et al. (2024)
Fomes fomentarius, Ganoderma lucidum, Pycnoporus sanguineus, Trametes hirsuta	Beech sawdust, spruce sawdust	Construction materials	Germany	Saez et al. (2021)
Fomes fomentarius, Pleurotus ostreatus	Wood chips from trees of beech, European oak, and pear	Construction materials	Germany	Moser et al. (2017)
Fomitopsis pinicola, Ganoderma carnosum, Pleurotus eryngii, P. ostreatus, Trametes versicolor	Wheat straw, pine sawdust, oak shavings, tree of heaven wood chips, shredded beech wood	Insulation	Italy	Charpentier-Alfaro et al. (2023)
Fomitopsis pinicola, Gloeophyllum sepiarium, Laetiporus sulphureus, Phaeolus schweinitzii, Piptoporus betulinus, Pleurotus ostreatus, Polyporus arcularius, Trametes pubescens, T. suaveolens, Trichaptum abietinum	Sawdust and shavings of birch, aspen, spruce, pine, fir	Insulation materials	Canada	Wimmers et al. (2019)
Funalia trogii, Ganoderma australe, Nothophellinus andinopatagonicus, Pleurotus ostreatus, Ryvardenia cretacea	Poplar sawdust	Biocomposites	Argentina	Aquino et al. (2022)
Ganoderma australe, Pleurotus ostreatus, Trametes versicolor	Molasses	Mycelium mats	Australia	Chulikavit et al. (2022)
Ganoderma curtisii	Guayule bagasse,	Insulation	Mexico	César et al. (2023)
Ganoderma fornicatum, G. williamsianum, Lentinus sajor-caju, Schizophyllum commune	Rubber tree sawdust, corn husks, rice straw	Biocomposites	Thailand	Aiduang et al. (2022b)
Ganoderma fornicatum, G. williamsianum, Lentinus sajor-caju, Schizophyllum commune, Trametes coccinea	Bamboo sawdust, corn pericarp	Interior designs	Thailand	Aiduang et al. (2024)
Ganoderma lucidum	Palm sugar fiber, cassava bagasse	Composite board	Indonesia	Agustina et al. (2019)
G. lucidum	PDB	Mycelium mats	Italy	Antinori et al. (2020)

Table 3 Continued.

Mushroom species	Main substrates	Intended application	Country	References
G. lucidum	Sawdust	Pure mycelium mats	Indonesia	Bahua et al. (2024)
G. lucidum	Sawdust (*Albizia chinensis*), empty fruit bunch fibres	Biocomposites	Singapore	Chan et al. (2021)
G. lucidum	Beech wood shavings, spelt flour, plaster dust	Electronic parts	Austria	Danninger et al. (2022)
G. lucidum	Cellulose fibre rapeseed bagasse	Insulation materials	Netherlands	Gauvin et al. (2021)
G. lucidum	Wood chips, sawdust, sugarcane, and cassava fibrous waste residues	Architecture design	Germany	Heisel et al. (2017)
G. lucidum	Cotton stalk	Biocomposites	China	Liu et al. (2019)
G. lucidum	MEB	Mycelium mats	France	Mazian et al. (2023)
G. lucidum	Hemp fibers, hemp hurds, pine wood sawdust, and silvergrass shavings	Building materials	Germany	Özdemir et al. (2022)
G. lucidum	Wheat straw polypropylene with bacterial spores	Thermal Insulation	Romania	Răut et al. (2021)
G. lucidum	Bamboo fiber	Biocomposites	Indonesia	Ridzqo et al. (2020)
G. lucidum	Bamboo fiber, chitosan	Biocomposites	Singapore	Soh et al. (2020)
G. lucidum	Sawdust	Biocomposites	USA	Travaglini (2019)
G. lucidum	Rapeseed straw, cellulose fiber	Insulation materials	Netherlands	Tsao (2020)
G. lucidum	Sawdust	Biocomposites	China	Wang et al. (2024)
Ganoderma lucidum, Hypsozygus ulmarius, Pleurotus citrinopileatus, P. cornucopiae, P. djmor, P. eryngii. P. ostreatus, P. pulmonarius, Polyporus brumalis, Stropharia rugosoannulata, Trametes versicolor	MEA, MEB	Biocomposites	Australia	Jones et al. (2018c)
Ganoderma lucidum, Pleurotus citrinopileatus, P. eryngii, P. ostreatus	Jute, cotton	Footwear products	USA	Silverman et al. (2020)
G. lucidum, P. djamor	Paste mixture of whole wheat flour, malt extract, xanthan gum, tartar, citric acid	Mycelium mats	USA	Crawford et al. (2024)
G. lucidum, P. ostreatus	Cellulose, PDB	Biofilms	Italy	Haneef et al. (2017)

Table 3 Continued.

Mushroom species	Main substrates	Intended application	Country	References
G. lucidum, P. ostreatus	Beech sawdust, oak sawdust, bleached cellulose pulp, shredded cardboard, shredded newspaper, cotton fibers, soy silk fibers, wheat bran, wheat straw, burlap, clay, sand	Biocomposites	Austria	Vašatko et al. (2022)
G. lucidum, P. ostreatus	PDB	Bio-scaffolds	Italy	Antinori et al. (2021)
Ganoderma lucidum, Pleurotus ostreatus, Polyporus squamosus	Canola straw, Cattail, hemp	Packaging materials	Canada	Rahman (2024)
Ganoderma lucidum, Trametes versicolor	Spent coffee grounds, coffee chaff, hay straw, hemp dust	Biocomposites	Romania	Barta et al. (2024)
G. lucidum, T. versicolor	Beech sawdust, spent mushroom substrate	Insulation materials	Germany	Schritt et al. (2021)
Ganoderma resinaceum	Waste rose flower, lavender straw	Biocomposites	Bulgaria	Angelova et al. (2021)
G. resinaceum	Miscanthus	Insulation materials	Luxembou rg	Dias et al. (2021)
G. resinaceum, Megasporoporia minor, Oxyporus latermarginatus	Wheat straw	Building insulation materials	UK	Xing et al. (2018)
G. resinaceum, T. versicolor	Hemp hurds, beechwood sawdust	Construction	Belgium	Elsacker et al. (2021)
G. resinaceum, T. versicolor	Beech wood sawdust, hemp fibres	Biocomposites	Belgium	Van Wylick et al. (2022)
G. sessile, T. ochracea, T. versicolor	Wood chips of Apple, Vines	Design and architecture	Israel	Attias et al. (2019)
Ganoderma sp.	Cotton byproducts	Packaging materials	USA	Holt et al. (2012)
Ganoderma sp.	Corn stover	Insulation materials	USA	Pelletier et al. (2019)
Ganoderma steyaertanum	Cardboard, coffee grounds	Biocomposites	Australia	Gough et al. (2024)
Irpex lacteus	Sawdust pulp of Alaska birch	Thermal Insulation material	USA	Yang et al. (2017)
Lentinula edodes	Coconut powder, wheat bran	Packaging	Brazil	Matos et al. (2019)
L. edodes (spent mushroom)	Sawdust (birch)	Biocomposites	Sweden	Berglund et al. (2024)
L. edodes, Pleurotus eryngii	Bagasse fibre	Fire retardancy	Iran	Hemmati & Garmabi (2012)
L. edodes, P. ostreatus	Sengon wood sawdust, bagasse	Biocomposites	Indonesia	Christos et al. (2024)

Table 3 Continued.

Mushroom species	Main substrates	Intended application	Country	References
Lentinus crinitus	Barley straw	Biocomposites	Mexico	César et al. (2021b)
L. sajor-caju	Rubber tree sawdust, corn husk	Biocomposites	Thailand	Jinanukul et al. (2024)
L. sajor-caju	Corn husk, rubber sawdust, paper waste	Biocomposites	Thailand	Teeraphantuvat et al. (2024)
L. velutinus, P. albidus, Pycnoporus sanguineus	*Pinus* sawdust	Packaging biofoams	Brazil	Bruscato et al. (2019)
N/A	Rice husk, wheat grain	Biocomposites	Malaysia	Arifin & Yusuf (2013)
N/A	Soil	Architecture design	Germany	Colmo & Ayres (2020)
N/A	Hemp fibres	Designs	USA	Dessi-Olive (2022)
N/A	Hemp fibres	Sound absorption	USA	Hsu & Dessi-Olive (2021)
N/A	Rubber tree sawdust	Construction materials	India	Finu et al. (2023)
N/A	Clay, sugarcane colasses, rice bran, sawdust, coconut husks	Construction materials	Philippines	Maximino et al. (2020)
N/A	N/A	Building materials and designs	Denmark	Özlü & Nicholas (2021)
N/A	Switch grass, rice straw, sorghum stalks, flax shive, kenaf, hemp	Acoustic absorption panels	USA	Pelletier et al. (2013)
N/A	Cotton burs, switchgrass, rice straw, sorghum stalks, corn stalks, kenaf	Insulation materials	USA	Pelletier et al. (2017)
N/A	Cotton hulls	Building materials	India	Santhosh et al. (2018)
N/A	Low-quality cotton, hemp shives	Biocomposites	Italy	Sisti et al. (2021)
N/A	Corn stover	Biocomposites	USA	Tudryn et al. (2018)
N/A	N/A	Electronic parts	USA	Vasquez & Vega (2019a)
N/A	N/A	Wearables	USA	Vasquez & Vega (2019b)
N/A	N/A	Biocomposites	USA	Islam et al. (2017)
N/A	N/A	Biocomposites	USA	Islam et al. (2018)
N/A	Jute, hemp, cellulose	Biocomposites	USA	Jiang et al. (2017)
N/A	Wood particles of spruce, pine, fir, cellulose nanofibrils	Packaging and furniture applications	USA	Sun et al. (2019)

Table 3 Continued.

Mushroom species	Main substrates	Intended application	Country	References
N/A	N/A	Pure mycelium mats	USA	Sun et al. (2021)
N/A	Cotton fiber, hemp pith	Biocomposites	USA	Ziegler et al. (2016)
Oudemansiella radicata, P. ostreatus	Cotton stalk, wheat bran	Biocomposites	China	Gou et al. (2021)
Phanerochaete chrysosporium	Malt extract	Biomedical use	India	Khamrai et al. (2018)
P. chrysosporium	PDA	Construction materials	USA	Menon et al. (2019)
Phellinus igniarius	Corn cob, wheat bran	Biocomposites	China	Wang et al. (2019)
P. djamor	Northern bleached softwood kraft fibres	Filtration, packaging, bioremediation	Canada	Ahmadi et al. (2022)
P. eryngii	Hardwood sawdust	Packaging	Canada	Kao et al. (2022)
P. eryngii	Sawdust	Shoe products	USA	Wolfe & Cao (2024)
P. eryngii, P. ostreatus, Pycnoporus sanguineus	Coconut powder, wheat bran	Packaging materials	Brazil	Teixeira et al. (2018)
Pleurotus florida	Spent mushroom, clay	Insulation materials	Egypt	Ali et al. (2023)
P. ostreatus	European beech sawdust	Biocomposites	Austria	Alaux et al. (2023)
P. ostreatus	Coffee husk, sawdust, sugarcane bagasse	Construction materials	Ethiopia	Alemu et al. (2022)
P. ostreatus	Hemp hurds	Biocomposites	USA	Etinosa et al. (2024)
P. ostreatus	Bamboo fibers	Indoor applications	Singapore	Gan et al. (2022)
P. ostreatus	Oakwood pellets, wheat straw	Building materials	USA	Ghazvinian & Gürsoy (2022)
P. ostreatus	Straw, sawdust	Architecture design	USA	Ghazvinian et al. (2019)
P. ostreatus	Sawdust, straw, hemp	Design, architecture	USA	Ghazvinian et al. (2022)
P. ostreatus	Glass wool, hemp wool	Biocomposites	Canada	Grenon et al. (2023)
P. ostreatus	Cotton seed hulls, carboxylated styrene butadiene rubber latex	Biocomposites	China	He et al. (2014)
P. ostreatus	Bagasse, sawdust, wheat bran	Packaging, insulation, furniture	India	Joshi et al. (2020)
P. ostreatus	Spent coffee grounds, pineapple fibres	Biocomposites	Thailand	Kohphaisansombat et al. (2023)

Table 3 Continued.

Mushroom species	Main substrates	Intended application	Country	References
P. ostreatus	Hemp stalks, rice straw, lacquer tree wood chips, oak wood chips	Air filtration panels	South Korea	Lee & Choi (2021)
P. ostreatus	Crop residue *(Triticum* sp.), edible films (carrageenan, chitosan, xanthan gum)	Packaging	Mexico	López Nava et al. (2016)
P. ostreatus	Rice husks, sawdust	Biocomposites	Uganda	Mbabali et al. (2023)
P. ostreatus	Waste cardboard	Biocomposites	USA	Mohseni et al. (2023)
P. ostreatus	Sugarcane bagasse, sawdust, rice husk	Biofoams	Malaysia	Nashiruddin et al. (2022)
P. ostreatus	Wood chips, hemp fibres	Designs	Germany	Nguyen et al. (2022)
P. ostreatus	Rice straw, bagasse, coir-pith, sawdust, corn straw	Packaging materials	China	Peng et al. (2023)
P. ostreatus	Hemp fiber, peanut shell	Biocomposites	Argentina	Picco et al. (2024)
P. ostreatus	Rice husk, wheat straw, rice husk powder, wood shaving, walnut shell	Biocomposites	Turkey	Sağlam & Özgünler (2022)
P. ostreatus	Vegetable peel, denim textile waste, coffee grounds, synthetic textile waste	Biocomposites	Spain	Sangosanya & Pistofidou (2024)
P. ostreatus	Merino wool, paper cellulose, barley straw	Architecture design	UK	Scott et al. (2020)
P. ostreatus	Rubber wood sawdust	Biocomposites	Malaysia	Shakir et al. (2020)
P. ostreatus	Rubber wood sawdust	Biocomposites	Malaysia	Shakir et al. (2023)
P. ostreatus	Coir pith, sawdust	Packaging materials	India	Sivaprasad et al. (2021)
P. ostreatus	Waste cardboard, paper, newsprint	Sound absorption	USA	Walter & Gursoy (2022)
P. ostreatus	Spent mushroom substrate (cotton seed hulls, corncobs, crayfish shells, wheat brans	Particle boards	China	Lu et al. (2024)
P. ostreatus	Rye berries	Insulation materials	USA	Zhang et al. (2022)

Table 3 Continued.

Mushroom species	Main substrates	Intended application	Country	References
P. ostreatus (spent mushroom)	Wheat straw	Thermal insulation	Chile	Aravena et al. (2024)
P. ostreatus, Polyporus squamosus, Volvariella volvacea	Hemp fiber, wood chips	Biocomposites	USA	Etinosa (2019)
Pleurotus ostreatus, Schizophylllum commune, Trametes multicolor	Fern (*Azolla filiculoides*)	Biocomposites	Netherlands	Läkk et al. (2018)
P. ostreatus, T. hirsuta	Pine and spruce shavings	Biocomposites	Finland	Kuribayashi et al. (2022)
P. ostreatus, T. ochracea	Beech sawdust, rapeseed straw, non-woven cotton fibre	Non-foam panels	Netherlands	Appels et al. (2019)
P. pulmonarius	Sugarcane bagasse, textile scraps	Sound absorption	Colombia	Garcia et al. (2023)
Polyporus brumalis, T. versicolor	Wheat straw, rice hulls, sugarcane bagasse, molasses	Nanofibers	Australia	Jones et al. (2019b)
Pycnoporus sanguineus	Coconut powder, wheat bran	Building materials	Brazil	Santos et al. (2021)
Schizophyllum commune	Minimal medium	Mycelium films	Netherlands	Appels et al. 2020
S. commune	Minimal medium	Pure mycelium mats	Netherlands	d'Errico et al. (2024)
S. commune (GMO)	Agar minimal medium	Mycelium mats	Netherlands	Appels et al. (2018)
T. betulina	Rapeseed straw, recycled cellulose	Building materials	Netherlands	Livne et al. (2022)
T. pubescens, T. versicolor	Beechwood sawdust	Biocomposites	Germany	Nussbaumer et al. (2023)
T. versicolor	Hemp shives, birch sawdust	Insulation materials	Latvia	Irbe et al. (2024)
T. versicolor	Flax (dust, long-treated fibers, untreated fibres, waste), wheat straw dust, wheat straw, hemp fibres, pine softwood shavings	Thermal Insulation	Belgium	Elsacker et al. (2019)
T. versicolor	Rice hulls	Fire-resistant panels	Australia	Jones et al. (2017)
T. versicolor	Rice hulls, glass fines	Construction materials	Australia	Jones et al. (2018a)
T. versicolor	Wheat grains	Insulation materials	Australia	Jones et al. (2018b)
T. versicolor	Pulp and paper mill sludge	Insulation materials	Chile	Muñoz et al. (2024)
T. versicolor	Yellow birch wood veneers	Biocomposites	USA	Sun et al. (2022)
T. versicolor	Spruce wood particles	Biocomposites	Slovakia	Vidholdová et al. (2019)
T. versicolor	Hardwood chips, hemp shives	Construction materials	Latvia	Zimele et al. (2020)

Note: N/A = not available. The taxon name is provided in the same way as in the published paper.

Mushroom-based biomaterials

Mushroom-based biomaterials (MBs) are derived from mushroom fruiting bodies rather than culture mycelium (Bustillos et al. 2020). These materials are also biodegradable, lightweight, and renewable, requiring minimal energy for their production and leaving a minimum footprint than synthetic plastics (Abhijith et al. 2018, Müller et al. 2021, Pylkkänen et al. 2023). MBs possess the structural properties of fungal tissues while exhibiting material characteristics comparable to mycelium-based biomaterials. Their composition consists of chitin, glucans, and protein, which contribute to their mechanical strength, hydrophobicity, and thermal stability (Bustillos et al. 2020). Additionally, the intrinsic antifungal and antibacterial properties of mushrooms are exhibited in the MBs products, providing resistance to degradation caused by alien fungi and bacteria (Bustillos et al. 2020). These qualities make MBs a sustainable and efficient material and a promising candidate in biomaterial development and other fields.

In the production of mushroom-based biomaterials (MBs), the mushroom fruiting bodies are initially harvested, then dried and processed into various desired forms, such as sheets, powders, or composite materials (Porter & Naleway 2022, Pylkkänen et al. 2023). These processed forms can be combined with biopolymers or natural fibres to create advanced, high-performance products. Alternatively, mushrooms can be cultivated directly in the mould until full growth, which is then harvested, dried, and treated. These MBs have also demonstrated significant potential in various applications, including constructions, textiles (e.g., vegan leather-like materials), and medical fields (e.g., wound dressings) (Hamlyn et al. 1994, Papp et al. 2017, Bustillos et al. 2020, Muhammad Rafiq et al. 2020, Müller et al. 2021, Porter & Naleway 2022, Pylkkänen et al. 2023). However, cultivating mushrooms to produce large quantities of basidiomata requires significant resources and time. Product consistency can also be a challenge, directly affecting their quality. MBs also require additional treatments to enhance hydrophobicity and resistance to microbial degradation. Although research in this field is limited, based on published articles, some research on MBs is provided in Table 4.

Table 4 Mushroom species whose basidiomata are utilized in the preparation of biomaterials.

Fungal species	Part used	Target use	Country	References
Agaricus bisporus	Stipe	Wound dressing	UK	Hamlyn et al. (1994)
Agaricus bisporus, Ganoderma lingzhi, Grifola frondosa	Whole basidiomata	Biocomposites	USA	Porter & Naleway (2022)
Fomes fomentarius	Whole basidiomata	Biocomposites	Germany	Pylkkänen et al. (2023)
Fomes fomentarius	Whole basidiomata	Construction materials	Germany	Müller et al. (2021)
Fomes fomentarius, Piptoporus betulinus	Whole basidiomata	Ethnomycological & ethnomedicinal use	Hungary	Papp et al. (2017)
Ganoderma boninense	Whole basidiomata	Construction materials	Indonesia	Muhammad Rafiq et al. (2020)
Phellinus ellipsoideus	Whole basidiomata	Leather	USA	Bustillos et al. (2020)

Major differences between mushroom-based biomaterials (MBs) and mushroom mycelium-based biomaterials (MMBs)

The key differences between mushroom-based biomaterials (MBs) and mycelium-based biomaterials (MMBs) are outlined as follows:

Parts used: MBs use the fruiting bodies directly in the development of biomaterials, while MMBs involve mycelium cultivation in feeding substrates under sterile and controlled conditions (Bustillos et al. 2020).

Production method: MBs utilize the natural growth characteristics of fruiting bodies. In this approach, fruiting bodies are cultivated directly within moulds until the ultimate shape and size (Müller et al. 2021, Pylkkänen et al. 2023). In contrast, mycelium-based biomaterials (MMBs) allow for the vegetative growth phase of the fungus. Mycelium is allowed to fully colonize lignocellulosic substrates, after which the colonized substrates are broken down into fine particles and transferred into moulds to allow further mycelium growth, resulting in products with specific shapes and dimensions (Khyaju & Luangharn 2024).

Challenges and future directions of mycelium-based biomaterials

In the current context, the use of mushroom mycelium in materials science is a fascinating innovation, particularly for developing environmentally friendly, sustainable materials. The MMBs have gained popularity as a sustainable measure in converting agricultural and forestry by-products into cost-effective, energy-efficient, and versatile materials. Consequently, these MMBs have been successfully applied to various sectors, including construction, packaging, architectural designs, textiles, and insulation (Al-Qahtani et al. 2023, Khyaju & Luangharn 2024). Additionally, the potential growth and development of the MMB sector is reflected by the increasing number of patent acceptances (Cerimi et al. 2019). Despite recent scientific advancements that have enabled the development and application of MMBs, several challenges remain to their widespread adoption and scalability. Based on existing literature, some of the key limitations of MMBs are briefly discussed below:

Misleading science: Research on MMBs is rapidly expanding, mainly in mycology and material science, and its constraints must be addressed (Ghazvinian & Gursoy 2022). Systematic identification of the mushroom species is crucial to ensure the reproducibility and reliability of results, including the MMB field. Employing a polyphasic approach for species-level identification, along with the use of the latest legitimate names, is essential for conducting scientific research and scaling up industrial production. Additionally, the MMBs products are designed to be people-centric, in the form of packaging, indoor insulation, wearables, and electronic parts. Therefore, these products require basic attention from users, both regarding health concerns and safety. Furthermore, emerging opportunities for MMBs applications include genetic modification of mushroom strains (GMO), such as through CRISPR/Cas9-based systems, to enhance specific characteristics (Amobonye et al. 2023, Salichanh et al. 2025). However, the absence of an international standardized set of parameters for MMBs development and material testing creates challenges in understanding and comparing material properties (Aiduang et al. 2022a). Establishing international standards for MMBs fabrication and evaluation would significantly improve the consistency and scientific integrity of the field.

Limited exploration of mushroom species: In the MMBs sector, research and industrial works focus on only a few mushroom species (Table 2). However, many recognized mushroom species are underexplored and underutilized for MMBs. Besides this, the hidden box of underexplored mushrooms in nature holds a huge opportunity. With the incorporation of phylogenetic analytical tools and micro- and macro-morphological characteristics, the discovery of novel fungal species has seen a sudden rise and is expected to increase further (Jeewon & Hyde 2016). Based on the selection criteria for MMBs, medicinal, edible, and saprobic mushroom species can be screened and utilized in future experiments to develop superior-quality MMB products (Sydor et al. 2022). Diversifying the fungal species in MBBs may provide more efficient, sustainable, and economically viable solutions.

Substrate concerns: MMBs development utilizes agricultural residues and forest by-products as basic feeding substrates for mycelium, which are rich in lignin, cellulose, and hemicellulose. Excessive use of these resources for MMBs might create competition for feed in animal husbandry. However, the trend of increasing agricultural production can address the availability of these by-products (Aiduang et al. 2022a). Additionally, exploring diverse lignocellulosic substrates, such as pineapple peel, forest shrubs, banana plant fibres, and cactus fibres, could be an additional alternative for MBBs.

Contamination risks: A major challenge is contamination of MMBs by unwanted fungi or bacteria due to failure in maintaining a sterile environment. Sterilization of substrates, equipment, moulds, and the workspace requires specific protocols and implementation. Sterile conditions require efficient equipment and technical expertise. The culture must be pure, viable, and vigorous. Mushrooms are rich in antimicrobial compounds against gram-positive and gram-negative bacteria (Alves et al. 2012). In some mushroom species, the intrinsic antimicrobial properties of mycelium can help to reduce bacterial and other fungal growth in the final products (Amobonye et al. 2023). For instance, *Phellinus ellipsoideus* contains bioactive compounds that confer resistance to bacterial and fungal contamination, including protocatechuic acid, protocatechualdehyde, hispidin, hispolon, phelligridin, and inoscavin (Li et al. 2017, Amobonye et al. 2023). Selecting species with strong antimicrobial characteristics can further minimize contamination risks.

Material characteristics: MMBs currently fall short in matching the mechanical strength, flexibility, water resistance, and durability of plastic-based products (Alaneme et al. 2023). Without proper treatment, MMBs are less fire-resistant than some synthetic materials, restricting their use to semi-structural and non-structural applications (Alaneme et al. 2023). To address these limitations, several efforts have been put forward, including reinforcing MMBs with wood or metals (Almpani-Lekka et al. 2021). Additionally, treatments such as plasticizers, crosslinking agents, and post-processing help address these issues, enhancing hydrophobicity, strength, and durability (Almpani-Lekka et al. 2021, Elsacker et al. 2023). Moreover, the diversity of mushroom species offers an opportunity to overcome these challenges and improve material performance.

Scaling-up production: Producing MMBs in large quantities and maintaining their consistent properties is a major challenge (Abhijith et al. 2018). This is feasible only by expanding the laboratory setup, which means industries. MMB production requires controlled environmental conditions, including temperature, relative humidity, aeration, incubation duration, and light exposure (Aiduang et al. 2024). The output of MMBs depends on mycelium growth, which is slower than that of synthetic material. However, the establishment of several industries for MMBs production has been a benchmark for further expansion. Additionally, contamination by unwanted fungi and bacteria is another challenge, mainly in the liquid-state surface fermentation method, requiring strict safety protocols during development (Gandia et al. 2021). Research into modifying growth conditions and ensuring a sterile environment could help mitigate this problem and enhance production efficiency. For instance, Crawford et al. (2024) introduced a method for cultivating mycelium leather on a paste medium, which could accelerate growth and ease harvesting.

Economic viability: Financial investors invest their money and resources in a business, entreprise, or company, only under the conditions of getting profits over time. The total cost in a company refers to the combination of initial capital investment and operational or administrative costs. A primary raw input in MBBs production is low-cost agricultural residues and forest byproducts. However, other investments, such as land, labour, infrastructure, and equipment, also play a significant role in decision-making prior to startup. Additionally, market introduction and expansion of MBBs are still challenging due to stakeholder resistance from other companies with similar final uses, such as synthetic packaging or building products. However, the development of superior-quality products and increasing public demand for sustainable products provide strong support for the MBB industry. Scaling production and improving the quality of MMBs can address these cost-related limitations, making them more economically competitive in the market.

Regulatory and market acceptance: Animal-based leather production has a significant economic impact, accounting for a market value of EUR 48 billion and producing 558,000 tons globally (FAO 2016, European Commission 2019). However, this industry has a negative environmental impact, causing greenhouse gas emissions and chemical pollution (Silva 2021). On the other hand, MMBs production is struggling to meet the safety and performance standards for applications in construction, packaging, and leather products. In addition, shifting industry and consumer perceptions and acceptance of MMBs remains time-consuming (Abhijith et al. 2018). Despite this, the demand for MMBs is increasing, and their effectiveness, such as thermal insulating biomaterials, is being recognized for maintaining suitable indoor environments (Al-Qahtani et al.

2023). To develop high-quality MMBs, extensive studies across a wide range of mushroom species, their production methods, and post-harvest treatments are required. With the success of MBB utilization, they can expand market coverage.

Limited applications: Compared to plastic-based products or animal-based leather, the range of applications for MMBs remains relatively limited. MMBs are developed from liquid-state surface fermentation (LSSF) or solid-state fermentation (SSF). The harvested mycelium-based leather has not reached the quality of animal-based leather in terms of tensile strength, flexibility, and durability. Other parameters of MMBs, such as hydrodynamic and mechanical strength, are below the standards of the traditional and synthetic plastic-based materials. However, the MMBs have been utilized in packaging, insulation, architectural designs, and leather substitutes (Gandia et al. 2021). Additionally, MMBs have also been successful in specialized fields, such as biomedical scaffolds and electronic parts (Vasquez & Vega 2019a, Antinori et al. 2021, Danninger et al. 2022). Notably, ongoing intensive research and development in MMBs hold the potential to enhance their quality and enlarge their applications.

Conclusions

The MMBs are an innovative application of mushroom mycelium to develop environmentally friendly, biodegradable, and sustainable materials as an alternative to traditional synthetic products. The current review provides a checklist of all mushroom species used in the development of MMBs, at both the experimental and commercial scales. Based on the current trend of MMBs applications, the potential of underutilized and unexplored mushrooms could provide bright future opportunities for the MBBs sector. This study also examined the challenges faced in the MMB sector in mushroom species identification, substrate selection, their development, characterization, and marketing, and also discussed the possible opportunities for further improvements in relation to science, nature, economy, and people. The overall analysis of contemporary challenges, public awareness, research efforts, and opportunities reveals an impactful MMB industry that can drive a better future.

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Accessibility of data

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

Conflicts of interest

The authors declare no conflict of interest.

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