The Microbe 8 (2025) 100439

Contents lists available at ScienceDirect

The Microbe

journal homepage: www.sciencedirect.com/journal/the-microbe

Mycelium-based bioproducts: A novel material for a sustainable economy – A comprehensive review

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ARTICLE INFO

Keywords:
Biomaterials
Biofabrication
Biotextiles
Composite materials
Circular economy
Fungal mycelium
Lignocellulose

ABSTRACT

The biodesign and biofabrication of biomaterials from lignocellulosic plant residues self-generated by fungal mycelium have emerged as a new material culture in the past two decades. This new material culture is based on alternative manufacturing paradigms that prioritize making new materials instead of extracting them. This culture integrates the basic principles of the circular economy and material biotechnology, ensuring their susceptibility to biodegradation and returning to their original state. Its implementation in manufacturing sectors aims to compete with animal-based leather, materials, and petrochemical products while promoting sustainable protein foods, reducing global environmental impact. This review explores the molecular and global aspects of new mycelial culture, focusing on the morphogenesis, chemical composition, and cellular integrity of fungi. It discusses the extracellular multienzymatic systems for lignocellulose degradation, the main substrates used, biomaterials developed from mycelium, biotextiles, materials, packaging and insulation products, new food sources, and art and architectural design. The review also highlights the current state of the art of the avant-garde companies promoting a circular economy based on fungal mycelium, replacing fossil resources with environmentally friendly materials, generating sustainable production cycles with low energy demand and environmental impacts, and promoting a new material consciousness.

1. Introduction

Materials have played a crucial role in human societies, shaping civilization through natural resources like wood, wool, leather, and cotton. However, the production of synthetic materials, such as plastics and polymers, has raised environmental concerns due to toxic waste production, high energy consumption, greenhouse gas emissions, increased atmospheric temperature, and concomitant global change (Cerimi et al., 2019). To address these issues, the scientific community and industry stakeholders are increasingly focusing on green technologies and material innovation. The development of bio-based and biodegradable materials, particularly those derived from renewable natural resources, has become a significant area of interest (Aiduang et al., 2024; Appels et al., 2019). Fungi have emerged as a promising resource due to their metabolic versatility, rapid growth, and capacity to convert agricultural and industrial waste into valuable bioproducts. Fungal-based biomaterials have gained significant interest in recent years due to their unique ability to colonize and bind together diverse organic substrates, forming lightweight, biodegradable, and structurally robust composite materials (Aiduang et al., 2024; Appels et al., 2019). These materials are increasingly viewed as sustainable alternatives to conventional materials like plastic, polyurethane foam, and animal leather. Biotechnology companies are transitioning to a circular economy by utilizing fungal and material biotechnology to develop high-value products, such as food additives, bioactive compounds, pigments, biofuels, enzymes, vitamins, and amino acids (Meyer et al., 2020; Niego et al., 2023). In recent years, the trend has shifted from developing fruiting bodies or bioactive molecules for medicinal purposes to studying fungal mycelium, offering sustainable alternatives with a positive environmental impact (Jones et al., 2020; Zhang et al., 2023).

These mycelium-based products are gaining popularity in the textile industry, achieving efficient, profitable, and competitive results against imperishable materials like petrochemicals and animal leather (Elsacker et al., 2019). Currently, mycelium-based products are revolutionizing industries, such as packaging, textiles, leather, construction materials, organic furniture, and automation (Aiduang et al., 2024; Elsacker et al., 2019). They also serve as thermal and acoustic insulation, fire protection, and new food sources with high amino acids and protein content (Fletcher, 2019; Khan et al., 2024). Nevertheless, the literature on mycelium-based biomaterials is biased and incomplete. Hence,

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https://doi.org/10.1016/j.microb.2025.100439
Received 14 April 2025; Received in revised form 26 June 2025; Accepted 30 June 2025

companies are focusing on the new mycelial culture to keep methodologies for obtaining fungal-based biomaterials encrypted. Therefore, this review aims to explore the symbiosis of the kingdom of fungi in generating biomaterials from lignocellulosic waste, focusing on the mycelium as the origin and morphogenesis, chemical composition, and cellular integrity. Moreover, it discusses the multienzymatic systems involved in lignocellulose degradation, major biomaterials made from fungal mycelium, and the international market and companies producing them.

2. Methodology

This review explores the development and application of mycelium-based bioproducts, analyzing literature from major academic databases, including Scopus, Web of Science, PubMed, and Google Scholar, published between 2009 and 2025. Keywords used in the search included terms like “mycelium-based materials,” “fungal biomaterials,” “mycelium composites,” “biodegradable,” “sustainability,” “lignocellulosic substrate,” and “fungal biotechnology.” The review identified a wide range of studies addressing the biological, chemical, and engineering dimensions of mycelium-based materials. The review used specific inclusion and exclusion criteria, including studies focused on the production, characterization, or application of mycelium-derived materials or providing theoretical or experimental insights into fungal physiology, substrate interactions, or biofabrication techniques. Only peer-reviewed journal articles and book chapters, written in English, were considered. The selection process involved initial screening of titles and abstracts, reviewing full texts, and manually extracting critical information. The review did not conduct a formal risk of bias assessment for individual studies, but preferred publications from reputable journals and those demonstrating methodological transparency. The synthesis of findings was conducted using a qualitative, narrative approach, focusing on key areas such as fungal biology, substrate utilization, material processing, mechanical properties, and sector-specific applications. The review also highlights emerging trends, identifies knowledge gaps, and discusses regional developments, particularly in Latin America and Asia, to provide a contextual framework for future research and innovation in sustainable biomaterials.

3. General characteristics of fungi

Fungi are a diverse and widespread group of eukaryotic organisms, including yeasts, molds, and mushrooms (Ivanova, 2022; Sydor et al., 2021; Zimele et al., 2020). Fungi have complex life cycles and can reproduce through sexual or asexual spore production or fragmentation of hyphae. During their life cycle, cells can be haploid, diploid, dikaryotic, or multikaryotic (Talhinhas et al., 2023). Many fungi, including *Armillaria bulbosa,* exhibit indeterminate and indefinite growth through asexual propagation (Meyer et al., 2020). Species from *Ascomycota* and *Basidiomycota* are homologous due to their dikaryotic cells, which result from the cytoplasmic fusion of cells for the distribution of two monokaryotic nuclei to daughter cells through mitosis (Hibbett et al., 2018).

3.1. Mycelium morphogenesis and cell integrity

The mycelium is a fibrous network of interconnected and dynamic microscopic filaments, which shows considerable plasticity and versatility, growing through apical extension and anastomosis (Fig. 1. b). It serves as the skeleton of an organism since it facilitates the quick transfer of water, sugars, and minerals, forming a closed system in response to external stimuli (An et al., 2022; Khan et al., 2025; Khan et al., 2021b; Yang et al., 2021). The mycelium can exhibit different physiological and biochemical activities depending on the species and the nutritional and local microenvironmental conditions (Antinori et al., 2020; Khan et al., 2021a, 2021c). When growing on a heterogeneous substrate, mycelium development remains diffuse, and long parallel structures or rhizomorphs are differentiated. In nutrient-dense environments, mycelium can exhibit pigmentation, rhythmic growth, thin and dense morphological sectors, and produce aerial structures (Fletcher, 2019).

Depending on their function and stage of development, there are two types of mycelia: the vegetative and aerial mycelium. The vegetative mycelium, found in soil, can colonize living plants and animals (e.g., parasitic fungi), decompose organic matter (e.g., saprophytic fungi), or form mutually beneficial relationships with plants (endophytic fungi, mycorrhizal fungi) (Fig. 1. c) (Vandelook et al., 2021). The aerial mycelium, originating from the substrate colonized by the vegetative mycelium, projects towards the surface through apical extension and branched propagation of aerial hyphae, forming tertiary structures at

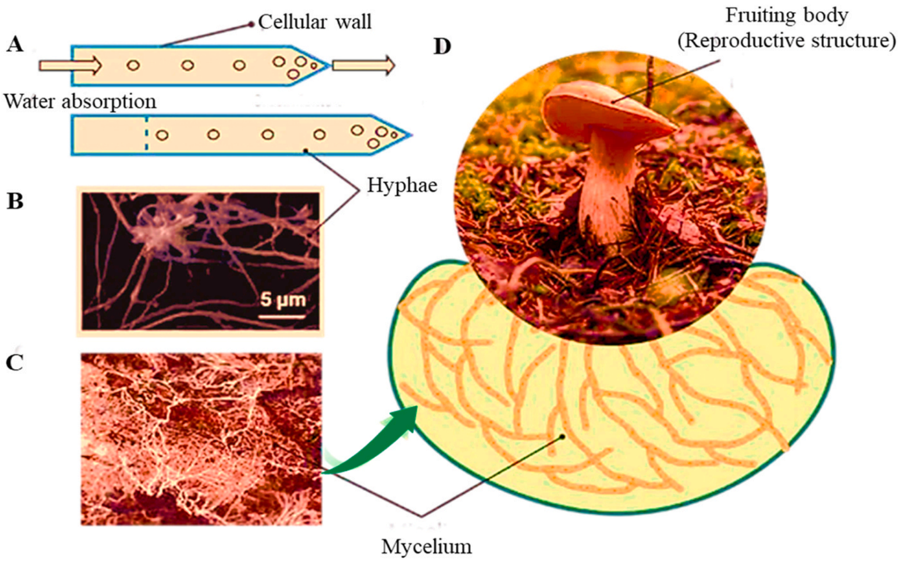

Fig. 1. Structure of fungal mycelium. (A) apical growth of hyphae generated by turgor pressure and osmotic gradient at the site of water absorption and extracellular material secretion via vacuoles, (B) TEM micrograph of *Ganoderma lucidum* (*G. lucidum*) on cellulose substrate, (C) mycelial colonization of a white rot fungus on lignocellulosic substrate, and (D) reproductive structure on vegetative mycelia.
Source: Haneef et al. (2017).

their tips that produce sexual or asexual spores (Costa-Rezende et al., 2020; Khan, 2024; Khan et al., 2024; Khan et al., 2021d). It is also recognized as a reproductive state of the fungus, as it ensures its survival and the transcendence of genes to new habitats (Fig. 1.d).

3.2. Structure and composition of the fungal cell wall

The mycelium has great mechanical, and hydrophobicity due to its cellular structure surrounding the plasma membrane, and its cell wall (Abo Elsoud and El Kady, 2019). The fungal cell wall plays a physiological role in morphogenesis and protection of the mycelium's integrity (Haneef et al., 2017). During cell growth, the cell contains a higher concentration of salts and sugars, generating an osmotic differential with the external environment and promoting the net entry of water through the plasma membrane, causing cell expansion (Alaneme et al., 2023; Jones et al., 2020). The plasma membrane is pressed against the inner surface of the wall, resulting in hydrostatic pressure or turgor (Yang et al., 2021). This increase in internal pressure allows the cell to approach a condition of homeostasis in which the influx of water coincides with the increase in cell volume during growth.

Thus, the fungal cell wall is a dynamic and constantly growing structure that resists expansion over its surface. Additionally, it is an intertwined and porous macromolecular structure assembled on the surface of the plasma membrane (Girometta et al., 2019). Generally, the cell wall consists of polysaccharides, chitin microfibrils, linear polymers of glycans, glycoproteins, lipids, polyphosphates, and inorganic ions (Fig. 2) (Ruiz-Herrera and Ortiz-Castellanos, 2019). Chitin synthase is responsible for the synthesis of chitin polymers, which are produced from β-1,4-N-acetyl-D-glucosamine monomers. These molecules are assembled in antiparallel matrices bonded by hydrogen, making them insoluble, tensile, and stress-resistant.

The β-1,3-glycosidic bond in glucans twists the polymer, forming a triple helix with hydrogen bonds. The β-1,3-glucans relate to β-1,6-glucans in the mature wall structure to produce a highly branched elastic network of polymers (Ruiz-Herrera and Ortiz-Castellanos, 2019). The structural proteins in the cell wall are glycoproteins with N- and O-linked carbohydrates. These include mannoproteins, which are glycosylated with mannose-rich chains, and other glycoproteins with mannose and galactose residues. These glycoproteins are connected to the plasma membrane by a glycosylphosphatidylinositol (GPI) anchor and cross-linked with chitin microfibrils and glucans, performing signaling and transport functions (Ibe and Munro, 2021; Utama et al., 2023). They participate in fusion with other cells and function in adhesion to surfaces, biofilm formation, and pathogenesis. They also mediate the absorption of compounds from the surrounding environment and protect cells from harmful substances.

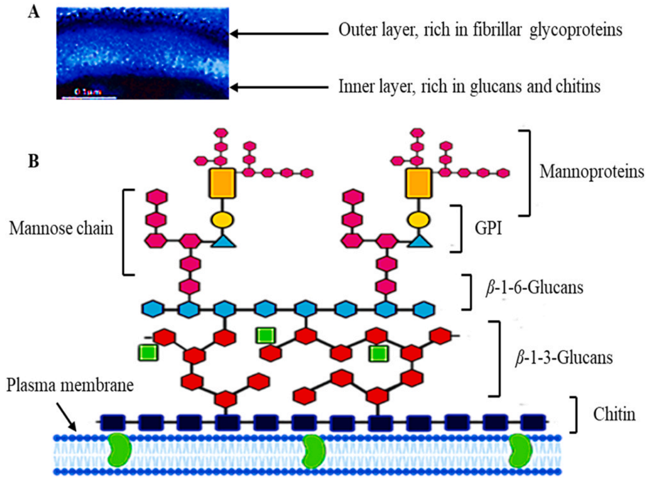

Fig. 2. Chemical composition of the fungal cell wall. **(A)** cell wall section of chemically fixed *Candida albicans* cells captured by transmission electron microscopy (TEM), **(B)** Schematic view of the general modular organization of the cell wall.
Source: Ruiz-Herrera and Ortiz-Castellanos (2019).

3.3. Variability in cell wall composition

Chemical analyses of cell wall composition revealed that the relative proportions of chitin, glucans, and glycoproteins vary according to the intrinsic physiological characteristics of the species (Garcia-Rubio et al., 2020; Ruiz-Herrera and Ortiz-Castellanos, 2019). The hydrolysis of fungal cell walls revealed that the most abundant sugars are glucose, glucosamine (hydrolytic product of chitin and chitosan), mannose, galactose, and galactosamine. Uronic acids, mainly glucuronic acid, pentoses (arabinose and ribose), and deoxyhexoses (fucoses) have also been found (Table 1). Exogenous factors, such as crop age, environmental conditions, growth media, nitrogen and carbon sources, ion concentration, temperature, pH, lighting, and the addition of different components, can influence the concentrations of cell wall components (Girometta et al., 2019).

Haneef et al. (2017) cultivate two white rot *Basidiomycetes* fungi, *G. lucidum* and *Pleurotus ostreatus* (*P. ostreatus*), in cellulose polysaccharides and potato dextrose broth (PDB), demonstrating that the fibrous films of mycelium can be tuned and controlled based on the substrate's nutrients. They also found that mycelium became more fibrous and stiffer when grown on pure cellulose. Pure cellulose is more complex and difficult to digest than PDB cellulose due to the presence of simple sugars. The rigidity of the mycelium is attributed to its increased synthesis of chitin, which aids in the penetration and degradation of cellulose (Vadivel et al., 2024).

4. Role of fungi in ecosystem and biomass recycling

Fungi are saprophytic organisms that recycle organic biomass and inorganic elements in the biosphere, maintaining continuous biogeochemical cycles of carbon, nitrogen, phosphorus, and sulphur. They obtain chemical energy and carbon from the degradation of pre-existing complex organic molecules through multienzymatic metabolic processes of polysaccharides, lipids, and insoluble proteins (Tchotet Tchoumi et al., 2019). Enzymes catalyze the depolymerization of macromolecules and can be classified based on their location as intracellular and extracellular, and function as hydrolases and oxidoreductases. Oxidative enzymes act cooperatively and synergistically, converting organic residues from dead organisms into monomers that are easily absorbed and transported (Fang et al., 2023). Specifically, saprophytic fungi that degrade plant biomass as woody materials rich in lignocellulosic sources, play a crucial role in the global carbon cycle by sequestering CO_2 and carbon mineralization (Tchotet Tchoumi et al., 2019).

The chemical composition of plant biomass varies, allowing for flexible structures like herbaceous materials or more resistant ones, such as tree trunks and branches. Lignocellulosic materials are recalcitrant systems due to the strong integration of three polymeric constituents: cellulose, hemicellulose (jointly called holocellulose), and lignin, providing structural support and resistance to plants' cell walls (Fang et al., 2023). These polymers are widely used in several industrial processes such as food production, paper/pulp, textiles, biofuels, detergents, and polymeric compounds. However, the rate and degree of lignocellulose degradation depend on ligninolytic enzymes as biological tools (Thapa et al., 2020).

4.1. Structure and recalcitrance of lignocellulosic biomass

Cellulose is one of the most abundant organic molecules on earth and constitutes approximately 45 % of the dry weight of wood. It is a linear homopolymer of D-glucopyranose linked by β-1,4 glycosidic linkages.

Table 1
Major carbohydrates identified in the fungal cell wall.

Taxonomic group	Glc	Gal	GlcN	Mann	GalN	Glucur	Rham	Fuc	Xyl	Ara
Chitridiomycota	+ +	+ ++	+	+	tr	0	tr	0	tr	+ /-
Zygomycota	+	+	+	0	0	0	tr	0	0	0
Hemiascomycota	+ +	+ +	+ ++	0	0	0	0	0	0	0
Euascomycota	+ ++	+ +	+ ++	+	0	0	+ /-	0	0	0
Heterobasidiomycota	tr	+	+	0	0	0	tr	0	tr	0
Homobasidiomycota	+ ++	+ ++	+	tr	0	0	+	+	0	0

Note: tr = traces, + /- = less than 1 %, + = 1.1–5 %, + + = 6–20 %, + ++ = more than 21 % of total sugars, **Glc** = glucose; **Gal** = galactose, **GlcN** = glucosamine, **Mann** = mannose, **GalN** = galactosamine, **Glucur** = glucuronic acid, **Rham** = rhamnose, **Fuc** = fucose, **Xyl** = xylose, **Ara** = arabinose. **Source:** Ruiz-Herrera and Ortiz-Castellanos (2019).

Each cellulose chain is linked to other chains by hydrogen bonds and van der Waals forces that provide rigidity (Garcia-Rubio et al., 2020; Ruiz-Herrera and Ortiz-Castellanos, 2019). Cellulose is considered amorphous, making different crystalline forms called cellulose I, II, III, and IV. Cellulose I is typically found in the cell wall. Hemicelluloses, like cellulose, have emerged as sources of carbohydrates. Hemicellulose, a polymer with a lower molar mass than cellulose, is more easily hydrolyzed due to its amorphous structure. They form a complex, branched polymeric structure with greater structural diversity, consisting of different sugar units, including xylan, xyloglucan, mannan, glucomannan, galactoglucomannan, and callose (Yu et al., 2022). Lignin is the most abundant aromatic polymer in the biosphere. It is a branched, amorphous, and heterogeneous polymer composed of phenylpropane units (*p*-curamil, coniferyl, and sinapyl alcohol) linked by various types of linkages. Structurally, it holds cellulose and hemicellulose together, filling, gluing, and reinforcing the entire structure. Elementary cellulose fibrils, 3–5 nm in diameter, combine to form microfibrils up to 20 nm in diameter (Sanchez-Salvador et al., 2021). In ecosystems, three groups of decomposers of lignocellulosic plant biomass are recognized, including saprophytic fungi of white rot, brown rot, and soft rot. Each group is classified according to the enzymatic degradative capacity of lignocellulosic biomass. Decomposition interactions involve various extracellular ligninolytic enzymes that break down polysaccharides of plant cell walls for further digestion. The extracellular multienzyme system of saprophytic fungi is produced in the rough endoplasmic reticulum of the hyphae and exuded into the surrounding medium through vesicles (Ivanova, 2022; Zimele et al., 2020). The fungus develops a strategy commissioned by an arsenal of hydrolytic enzymes and oxidoreductases, producing free hydroxyl radicals, and lytic polysaccharide monooxygenase (LPMO) (Daly et al., 2021; El-Gendi et al., 2021).

4.2. Enzymatic degradation of lignocellulosic biomass

The degradation of lignocellulosic biomass is carried out by a mixture of enzymes, including cellulases, hemicellulases, pectinases, and extracellular oxidative enzymes that act cooperatively and synergistically (Nargotra et al., 2022). Table 2 summarizes the enzymatic activity of certain white rot fungi in solid-state fermentation substrates for 14 days. Cellulases catalyze the hydrolysis of β-1,4 glycosidic bonds that hold cellulose chains together, classified as endoglucanases, exoglucanases, and β-glucosidases (Thapa et al., 2020). Hemicelluloses are specific enzymes that depolymerize hemicelluloses, with the xylanases being the most studied and abundant enzymes. Among the xylanases, β-1,4-endoxylanases hydrolyze β-1,4 linkages, while β-xylosidases hydrolyze xylooligosaccharides formed by the endoxylanases (Mendonça et al., 2023; Pozo-Rodríguez et al., 2022). Moreover, the branches present in xylan are hydrolyzed by the enzymes α-L-arabonofuranosidase, α-glucuronidase, acetylxylan esterases, and feruloyl esterases. Pectinases are a group of enzymes that degrade pectin and branched polysaccharides in plant cell walls. Its main structure is composed of D-galacturonic acid, with side chains of xylose, galactose, or arabinose (De Souza, Kawaguti., 2021; Zheng et al., 2021). Due to its chemical resistance and structural complexity, the depolymerization of lignin is catalyzed by nonspecific extracellular enzymes with high oxidative power. These enzymes are grouped into laccase (Lac) and peroxidase enzymes such as lignin peroxidase (LiP), manganese peroxidase (MnP), and hybrid enzymes known as versatile peroxidases (VP) (Naranjo-Briceño et al., 2019).

The group of white rot fungi is known for their high capacity to degrade lignin, cellulose, and hemicellulose polysaccharides due to their highly active extracellular enzymatic system (Naranjo-Briceño et al., 2019; Nguyen et al., 2022). The ligninolytic potential of white rot fungi to degrade and digest the plant cell wall makes it one of the main microorganisms considered for obtaining mycelium-based biomaterials (Tables 2 and 3). The inoculation of white rot fungi in solid organic substrates results in a light composite, consisting of a three-dimensional intertwined network of natural reinforcing fibers and filamentous mycelial cells (Mueller et al., 2022; Srivastava et al., 2025). The organic material is usually degraded and replaced by fungal biomass, creating a spongy or compact layer that interweaves substrates with natural and synthetic supports, such as paper, jute, cotton felt, fiberglass, metal, and carbon. This process is used for obtaining products for packaging and insulation, biotextiles, and construction materials for homes (Atiwesh et al., 2022). The ligninolytic potential of fungal strains is expected to enhance their colonization ability on the lignocellulosic substrates (Atiwesh et al., 2022).

Table 2
Enzymatic activity of white rot fungi grown on a solid substrate for 14 days.

Species	Substrate	MnP	LiP	Cellulase	Hemicellulase	Reference
G. applanatum	Wheat straw	90.363	0	–	76.692*	Dinis et al. (2009)
Trametes versicolor	Wheat straw	66.69	0	–	27.675*	Knežević et al. (2016)
G. applanatum	Sawdust and poplar chips	73 Â± 7	0.33 Â± 0.04	1.15 Â± 0.2	2.2 Â± 0.2	Giorgio et al. (2012)
G. lucidum	Sawdust and poplar chips	7.7 Â± 0.6	1.50 Â± 0.04	0.75 Â± 0.2	2.0 Â± 0.2	Giorgio et al. (2012)
P. fomentarius	Sawdust and poplar chips	7.8 Â± 0.8	0.46 Â± 0.03	1.25 Â± 0.2	1.3 Â± 0.2	Giorgio et al. (2012)
P. fraxinea	Sawdust and poplar chips	13 Â± 1	0.22 Â± 0.022	0.8 Â± 0.3	1.8 Â± 0.3	Giorgio et al. (2012)

MnP: Manganese peroxidase activity (U/mgP)
LiP: Lignin peroxidase activity (U/mgP)
Lacasa: Laccase activity (U/mgP)
Celulasa: Cellulase activity (U/mgP)
Hemicellulase: Hemicellulase activity (U/mgP)

Table 3
Publications, production, and processing methods of mycelial composite materials.

Species	Substrate	Sterilization/ Pasteurization	Inoculation	Incubation	Drying	Product	References
P. ostreatus	Wheat grains	Boil water 100 °C + H_2O_2 (0.3 %)	10–20 % of SFS (esethene)	Total darkness 90–100 % HR, ambient temperature, 30 d	Oven drying at 125 °C for 2 h	Foam	Aranda-Calipuy et al. (2023)
G. lucidum *P. ostreatus*	Cellulose, cellulose-PDB	Autoclave at 120 °C for 15 min	Agar plates	25–30 °C, 70–80 % HR, 20 d	Oven at 60 °C for 2 h	Fibrous layers	Haneef et al. (2017)
Irpex lacteus	5 mm wheat barley, saved from milk, saved from grain, natural fibers, and $CaSO_4$	Pasteurization	Agar plates	14–42 d	Oven at 60 °C for 24 h	Foam	Yang et al. (2017)
T. versicolor	Linen powder, treated linen fibers, untreated linen fiber, linen wastes, wheat straw powder	Autoclave at 121 °C for 20 min	70 % dry substrate, 20 % autoclave water, demineralized, 10 % SFS (grain mixture)	28 °C for 8 d in mold, 8 d out of mold	70–100 °C for 5–10 h	Thermal insulation	Holt et al. (2012)
G. lucidum	Collect coffee beans, wooden sticks, grain mixing, and quinoa grain	Autoclave for 30 min	Inocule in PDYA	23–30 °C for 14 d	Oven-dried at 120 °C	Aerospace architecture	Rothschild et al. (2019)
T. versicolor	Yute matrix, PDB	Autoclave for 30 min	Inocule in PDA	25 °C, every 2–3 days, moisten the matrix with PDB, 30 days	Gluconate 15 h, coating of soy protein, distilled water (10 % P/P), and NaOH 2.5, pH 10, Hit 80 °C 30 min, Dry in the environment 15 h	Micotextiles	PM Tavares et al. (2017)
P. ostreatus	Non-woven cotton fiber (RH 55 %), Hae shrimp, rapeseed 1–3 cm, and saved (RH 65–70 %)	Autoclave	SFS	25 °C for 14 d in mold, 10 d out of mold, Darkness	Pressure 150 °C or cold 20 °C, 20 min, materials exposed to resin, dried for 24–48 h at room temperature	Foam	Jiang et al. (2019)
P. ostreatus	Biotex Jute, Biotex flax, Cellulose BioMid	Autoclave	Core: SFS, Kenaf, and hemp (1:1), 120 g, two layers of fiber	Inside polypropylene heads, 24 °C, 5 days, HR 98 %	Oven at 82 °C for 12 h, thermal pressing at 250 °C for 20 min, and resin coating.	Sandwich-type structures	Nguyen et al. (2022)
Pycnoporus sanguineus *P. albidus* *L. velutinus*	*Pinus* sp. 94 %, salted from ground wheat 5 %, 1 % calcium carbonate ($CaCO_3$)	Autoclave for 180 min	SFS	24 ± 2 °C	Oven at 80 °C for 24 h	Foam	Bruscato et al. (2019)

SFS: Sterilization/fermentation solution
RH: Relative humidity
PDYA: Potato dextrose yeast agar
PDA: Potato dextrose agar
PDB: Potato dextrose broth
PET: Polyethylene terephthalate

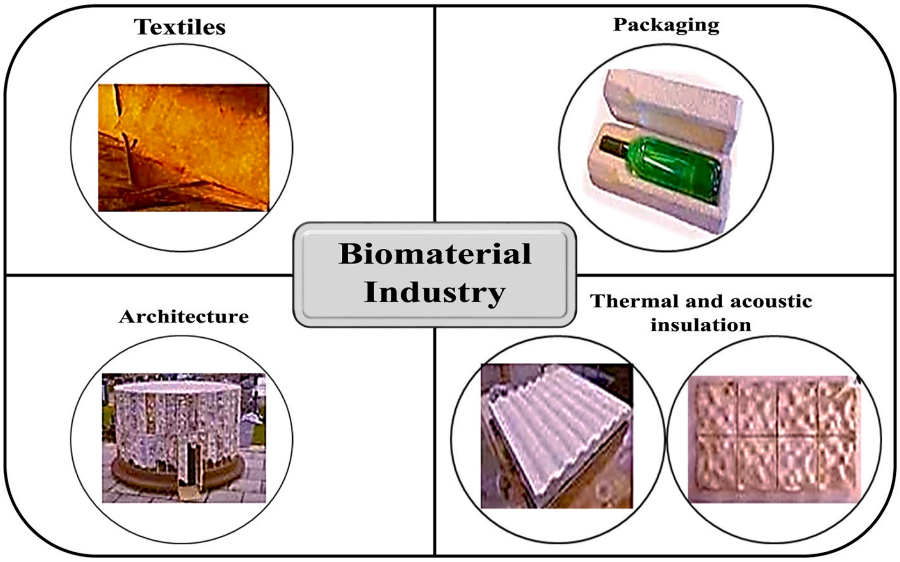

Fig. 3. Composite materials of fungal mycelium used in the industry.

5. Mycelium-based biomaterials

New changes prompt reconsideration, leading to fossil archetypes of thought and bioethical patterns that contradict the right to life. The emergence of a new material culture that integrates the principles of a sustainable economy necessitates addressing bioethical and technological challenges (Quiroz, 2025; Singh et al., 2024). Material biotechnology, a multi-inter and transdisciplinary field, emerged spontaneously, combining art and science with a "Sophist" cohesion, demonstrating a clear synergy between these fields (Almpani-Lekka et al., 2021; Gandia et al., 2021). In this context, Material Biotechnology is the rational use of biodiversity to convert natural materials, compounds, or organic waste into biodegradable products beneficial for society, art, and culture (Ashokkumar et al., 2022). Biomaterials are functional materials that have been designed and constructed from biological raw materials like plants, algae, bacteria, fungi, and microbial biopolymers (Biswal et al., 2020; Ghassemi et al., 2021).

These biomaterials may or may not be mixed with natural materials, compounds, or organic waste. They are self-generated by living organisms and are based on alternative manufacturing paradigms. These materials integrate the principles of the circular economy and Material Biotechnology, ensuring their susceptibility to degradation and returning to their original state in nature. The production processes of biomaterials must ensure that they do not compromise or harm the environment at all scales and throughout their value chain (Ghassemi et al., 2021). Radial Biomaterials (@radial.bio) identifies two major classifications of biomaterials: bio-based, which has a percentage of biological composition in its structure, and bio-manufactured, which uses living microorganisms as raw material or during the manufacturing process. The last type of biomaterial, which is also bio-based, is characterized by its growth, adhesion, and molding at the expense of living organisms (Fig. 3). Moreover, the final product should be of appropriate mechanical strength, easy to manufacture, and produced on a large scale. Lignocellulosic substrates are highly suitable for developing biomaterials derived from fungal mycelium (Elsacker et al., 2019).

Mycelium-based composites result from vegetative and/or aerial mycelial growth on organic materials such as agricultural waste (Appels et al., 2019). Among the most commonly used substrates are agro-industrial, forest residues, and residual biomass of primary and secondary forests (Table 3). Fungal mycelial growth is influenced by the substrate's nature and processing, growth parameters, nutritional requirements, and the genetic characteristics of the fungus being used. These parameters are crucial for determining colonization level, mycelium thickness, rigidity, flexibility, tensile strength, and hydrophobicity (Appels et al., 2019). Additionally, the physical condition of a substrate is crucial for the performance and structural properties of biomaterials derived from mycelial growth. Mycelial-based materials require specific physical conditions such as O_2 and CO_2 levels, relative humidity, light exposure, airflow, and temperature. The classification of mycelial development depends on whether it is derived from the vegetative or aerial mycelium, as explained below (Cerimi et al., 2019).

6. Biomaterials derived from vegetative mycelium

Biomaterials derived from vegetative mycelium on lignocellulosic substrates are categorized into foam and sandwich types.

6.1. Mycelium-based foams (MBFs)

Mycelium-based foams (MBFs) are biomaterials of low density, porous, and highly anisotropic, whose mechanical properties vary based on the directions of applied force. Apart from bricks and mycelium panels, they do not need pressing (hot or cold). The main substrates mentioned in the literature are fibers, husks, or wood pulp with particles of 5–25 mm in diameter. Its incubation takes place in a relatively humid microenvironment of 70–78 %, with a temperature of 24–28°C, without light, irrigation, or chemical inputs (Appels et al., 2019; Ruiz-Herrera and Ortiz-Castellanos, 2019). Following mycelium colonization, the substrate undergoes heat and pressure to deactivate mycelium and reduce humidity to 10–15 %, resulting in materials with properties similar to expanded polystyrene foams, suitable for packaging, thermal or acoustic insulation, and construction materials (Elsacker et al., 2019; Ross et al., 2020). Appels et al. (2019) presented an experimental design with *P. ostreatus* and *Trametes versicolor* (*T. versicolor*) species inoculated in substrates of straw, sawdust, and cotton, achieving significant differences in the mechanical performance of composite materials depending on the substrate and manufacturing process.

Cotton-based materials were less stiff and more resistant to moisture than straw-based composites. Heat pressing significantly increased material density (0.35–0.39 g/cm3), homogeneity, tensile strength (0.15–0.24 MPa), and stiffness, regardless of the substrate and the strain used. Additionally, the biomaterial presented significant similarity with polystyrene foams, cork, and wood in terms of density and longitudinal elasticity modulus or Young's Modulus (35–97 MPa) (Appels et al., 2019; Gandia et al., 2021). Moreover, the biomaterials self-generated by the laccase super-producing strain *Pycnoporus cinnabarinus* exhibited

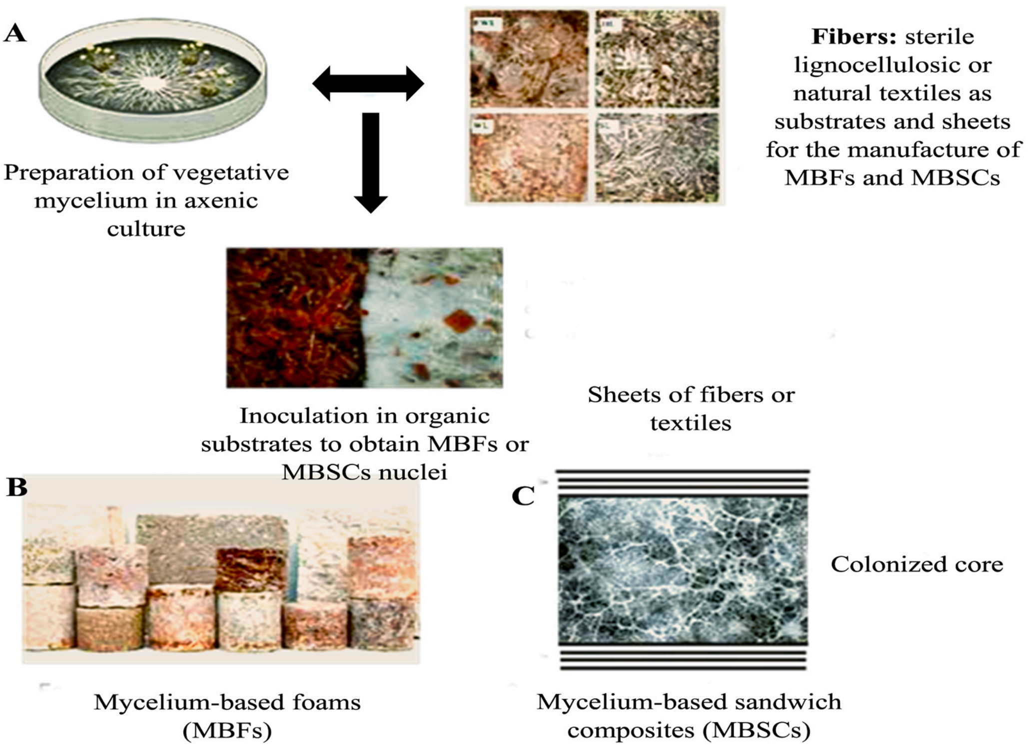

Fig. 4. Schematic representation of the production and morphological diversity of mycelium-based biomaterials (MBMs). (A) Fungal growth on an agar plate (B), Mycelium growth on various lignocellulosic substrates, (C) Early-stage colonization of shredded plant fibers by mycelium.

excellent elasticity and cushioning, making them suitable for packaging. These materials offer manufacturing advantages of these materials including low density, competitive resistance, mechanical properties of traction, impact, and stability at high temperatures (Fig. 4) (Ruiz-Herrera and Ortiz-Castellanos, 2019). Ultraviolet (UV) radiation makes these materials competitive with synthetic (polystyrene foam), biological, and nanostructured materials (Elsacker et al., 2019; Mueller et al., 2022).

6.2. *Mycelium-based sandwich composites (MBSCs)*

Mycelium-based sandwich composites (MBSCs) consist of a core covered by two or more dry, sterilized, and pre-impregnated layers made of lignocellulosic fibers or natural textiles (linen, jute, or cellulose) tailored to achieve the desired shape of the product (Ruiz-Herrera and Ortiz-Castellanos, 2019). The mycelium is inactivated through thermal pressing and cured with natural resin as detailed in Jiang et al. (2019) seven-step manufacturing system. The mycelium's natural cohesive action acts as a self-assembling glue, resulting in a single block. The use of flax sheets enhances colonization efficiency and biomass production. Generally, MBSCs are stronger and more rigid structures with a higher modulus of elasticity and tensile strength than MBFs due to the heterogeneity between the laminated layers and core. This manufacturing category is used for producing biotextiles. Under controlled conditions, physical, mechanical, and thermodynamic properties, including morphology, density, texture, appearance, growth kinetics, tensile and flexural strength, thermogravimetry, and water and humidity absorption, are factors that must be evaluated (Benson et al., 2019; Elsacker et al., 2019). Appels *et al.'s* (2019) study reveals that heat pressing enhances the homogeneity, strength, and stiffness of materials like foams, corks, or wood, thereby improving their performance. Specifically, renewable mycelium-based materials grown on straw are stiffer and less resistant to moisture than cotton-based composites (Appels et al., 2019). Currently, Ecovative Designs LLC manufactures MycoBoard™, a mycelial wood with a lower density (0.685 g/cm3) than glass panels and polyester (1.522 g/cm3) (Jones et al., 2020). Mycelium panels are stronger, machinable, customizable, and fire-resistant.

The National Aeronautics and Space Administration (NASA) is exploring mycotecture, proposing new concepts of aerospace architectural design based on compounds of vegetative fungal mycelium. The idea is to use organic waste generated by the crew, water, regolith (loose rocky materials from soil weathering), and inactive mycelial plates to produce self-adjusting, lightweight, fibrous materials with virtuous mechanical properties (Montana-Hoyos et al., 2022; Rothschild et al., 2019). Among its uses, NASA considers panel manufacturing, radiation protection, vapor seals, vehicle and furniture frames, and fire retardants. Likewise, NASA proposes that fungal materials be complemented with bacteria such as *Bacillus subtilis* to generate a mutualistic relationship allowing structural integrity (Sowmeya and Sathiavelu, 2024). Additionally, the study proposes using fungi as biosensors to detect pressure and failures in spacecraft by measuring mechanical stress through color or fluorescence changes.

7. Biomaterials derived from lignocellulosic and aerial mycelium

Since 3350–3100 BC, *Piptoporus betulinus* and *Fomes fomentius* species' fruiting bodies have been utilized as tinder material and for spiritual purposes (Jones et al., 2021). Over the years, *F. fosterius* has been used in various applications, including the production of biotextiles, such as hats, belts, bags, frames, and cleaning cloths for glasses. These mushrooms are harvested and cut into strips after the radial growth of fruiting bodies and stored in wooden boxes for 2 weeks before use. Airborne fungi develop their fruiting body from aerial mycelium for reproduction and spore dispersal. Their hyphae contain morphogenetic proteins that colonize the substrate, forming a spongy or compact layer called "fungal skin" (Appels et al., 2019). This layer is considered an alternative to animal leather due to its malleability, homogeneous aerial growth, biodegradability, and lack of tanning processes or polluting reagents.

Table 4
Mycelium-based companies and their products.

Company	Location	Material specifications	Reference
Food			
Ecovative Design LLC	New Jersey, United States	Vegan edible mycelium, rich in essential amino acids and nutrients, mimicking the shape and texture of Atlast™	Jones et al. (2020)
Isolation and packaging			
Ecovative Design LLC	New Jersey, United States	MycoComposite™ packaging foams, Mycoflex™ pure mycelium foams used in the production of insulating jackets, thermal coats, and shoes	Jones et al. (2020)
Mogu	Inarzo, Italy	Modular acoustic panels, Mogu™	Cerimi et al. (2019)
Ford Global Technologies LLC	Michigan, United States	Mycelium foam molded parts for vehicle interior equipment	Finnigan et al. (2019)
Radial Biomaterials	Jalisco, Mexico	Materials tailor-made for packaging and packaging	Colmenero Fonseca et al. (2024)
Loop Biotech	JD Delft, Netherlands	Loop Cocoon™ coffins, made from mycelium and organic waste, with moss inside for extra insulation	Berge (2024)
Biotextiles			
MycoWorks Inc.	California, United States	Reishi™	Williams et al. (2022)
Bolt Threads	California, United States	Sustainable alternative to animal leather: Mylo™	Jones et al. (2020)
Mycotech Lab	Bandung, Indonesia	Mylea™ Micellar Leather	Williams et al. (2022)
Le Qara	Peru	Le Qara, biodegradable microbial leather	Berge (2024)
Spora Biotech	Chile	Sustainable Mycelium Leather Sporatex™	Berge (2024)
Mycel Project	Republic of Korea	In collaboration with the Hyundai Motor industry, working on the development of mycelium materials that can replace leather and film	Amobonye et al. (2023)
Architecture and art			
Ecovative Design LLC	New Jersey, United States	MycoBoard™ construction panels used in architectural designs Kits and manuals used for mycelium-based biomaterials	Jones et al. (2020)
Mycomaker	Quito, Ecuador	Mycology kits, advice on producing mycelium-based biomaterials. New material culture educational programs	Manan et al. (2022)
Radial Biomaterials	Jalisco, Mexico	Industrial design or interior design products	Colmenero Fonseca et al. (2024)
Mycel Project	Republic of Korea	Interior design and manufacturing of lamps and decorations	Amobonye et al. (2023)

Several biotechnology-based companies worldwide are taking an interest in the aerial mycelium's potential to produce materials similar to leather. MycoWorks Inc., Bolth Threads, and Mycotech Lab are pioneers in producing alternatives for the textile industry, particularly leather (Jones et al., 2021; Williams et al., 2022). Mycelial leather has a similar appearance and properties to bovine and synthetic leather. MycoWorks Inc. claims to produce mycelial leather with superior properties compared to animal leather. For this, the modulation of aerial mycelium growth with aesthetic characteristics and/or quality thickness can be achieved from vegetative growth, the selection of the modulating organism, and its homogeneous distribution on the substrate (John, 2022; Vandelook et al., 2021).

On the other hand, Mycotech has launched a range of products, including shoes, handbags, and watch straps made using mycelium-based leather substitute MyleaTM. Its biodegradable leather (natural brown and naturally dyed black) has similar mechanical properties, including tensile strength (8–11 MPa), elongation (22–35 %), and tear strength (24 N) (Chase et al., 2019). Bolt Threads offers its mycelium-based product called MyloTM, which consists of natural layers of mycelium fiber directly adhered and compacted for a solid bond. However, the scientific community has limited information on mycelial leather replication. Similarly, the BioFab project aims to democratize knowledge about biomaterials by developing textiles made from mycelium and natural fibers. The mycotextile was made from homogeneous mycelium of *T. versicolor* and *Neurospora crassa* (*N. crassa*) on a vegetable fiber matrix (jute) and submerged in a PDB liquid culture medium. One point to consider is that the culture necessitates a daily supply of liquid medium every 2–3 days to maintain humidity in the mycelium. Recently, aerial mycelium has also been used as a mycoprotein, a nutritious food source, high in amino acids and fiber, and low in saturated fat, cholesterol, sodium, and sugar (Finnigan et al., 2019; Khan et al., 2024). Its structure and texture resemble meat due to its similarity to fiber size. AtlastTM, developed by Ecovative Design LLC, is a consumer product that uses mushrooms to imitate animal cuts like bacon, fillets, and chicken breasts. The mycelium forms structures at the micron level with extreme precision, resembling meat. QuornTM, another product recognized in 17 countries worldwide, uses mycelium manufacturing in 40-meter air fermenters, continuously fed with water, salts, and glucose from wheat or corn starch (Finnigan et al., 2019). These products offer a healthy and palatable alternative to traditional meat products.

8. Industrial applications and global trends

Pioneering companies in the mass production of fungal mycelium composite materials maintain confidentiality about technical details and physical characterization, and mechanics of biomaterials. Generally, the production technologies for biomaterials are currently in their incipient and developmental state, with the first reference being made in 2017. To date, there are 48 registered patents or patent applications for the use of fungal materials in various fields (Cerimi et al., 2019). Table 4 presents companies worldwide that use fungal mycelium in commercially designed products.

The fungal mycelium biomaterials biomanufacturing industry is dominated by Ecovative Design LLC (USA) with 45 % of patents followed by Ford Global Tech (USA) (19 %), Shenzhen Tech (China) (17 %), MycoWorks Inc. (USA) (6 %) and Spora Biotech (Chile) (0.48 %). These patents are mainly distributed in the United States (60 %) and China (30 %) (Meyer & Mengel, 2024). Of the above-mentioned companies, MycoWorks Inc. and Ecovative Design LLC have developed a biomaterial called "fungal leather" for the biotextile industry. In 2017, MycoWorks Inc. introduced textile biomaterial, followed by Ecovative Design LLC developing mushroom leather and selling the license to "Bolt Threads," a San Francisco-based start-up in sustainable textiles. Bolt Threads launched a Kickstarter campaign in 2018 for a bag made from mushroom leather called "Mylo," which was delivered in early 2020. Today, Bolt Threads is projected to use "MyloTM" as its highest-scale textile biomaterial and plans to have a pilot plant with a production capacity of 1000,000 square feet per year (Amobonye et al., 2023).

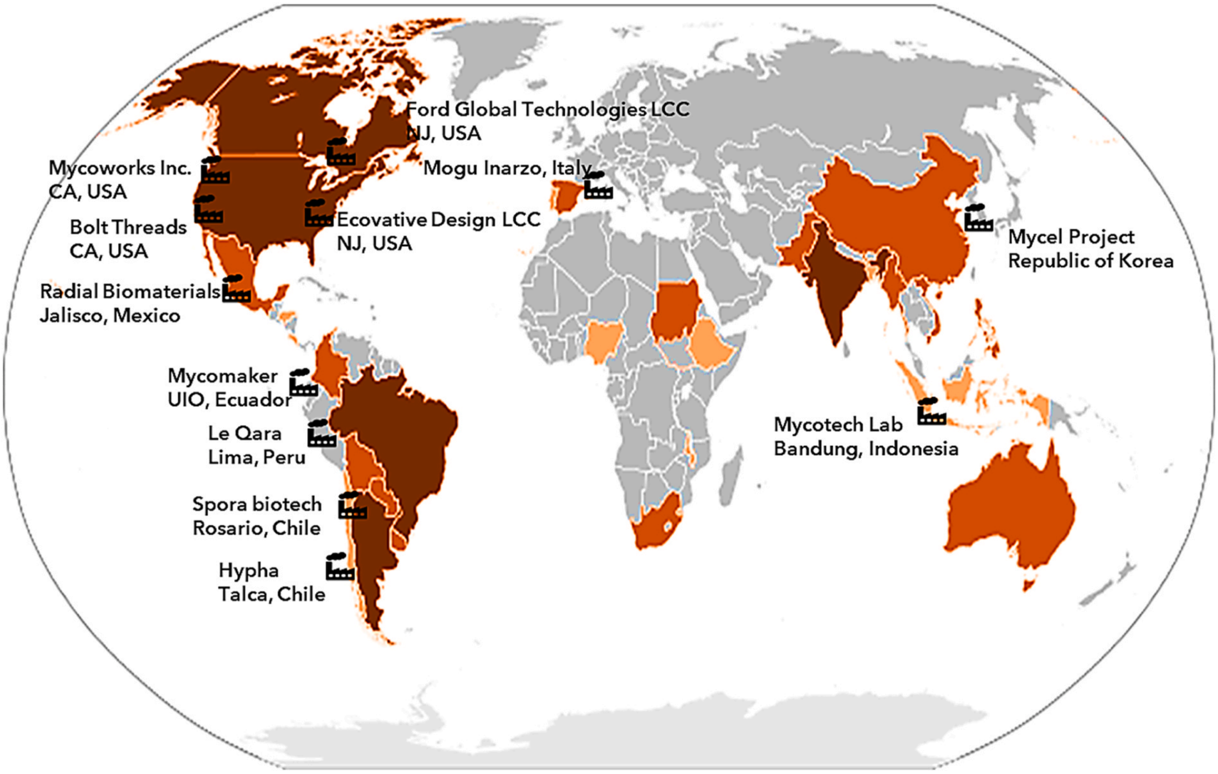

Fig. 5. Global industries and laboratories using fungal mycelium in food manufacturing, biotextiles, insulation, packaging, art, and architecture.

On another hand, MycoWorks Inc. launched a new product called "Made with Reishi" at New York Fashion Week 2020 using the material "ReishiTM" and the technology "Fine Mycelium." Subsequently, the company closed an investment round for $17.5 million, allowing its manufacturing operations to meet the growing demand for its ReishiTM material. Currently, the company operates two production facilities and plans to open a third commercial plant with a production capacity of 80,000 ft2 per year to launch luxury products (Amobonye et al., 2023). Similarly, Mycotech, an Indonesian company, produces MyleaTM, a fungus leather made from fungus, but it is not registered in the international intellectual capital system. The new mycelial culture is gaining traction in Latin America (Fig. 5), with start-ups emerging and companies consolidating. For example, Peruvian company Le Qara produces a biotextile made from symbiotic associations of microorganisms, while Spora Biotechin, Chile develops fungal mycelium leather under the Sporatex trademark (Amobonye et al., 2023; Berge, 2024). Likewise, Mycomaker from Ecuador, Hypha from Chile, and Radial Biomaterials from Mexico are focusing on producing bio-products for packaging, isolation, and mycotecture kits, providing advice on mycelium-based biomaterial manufacturing and promoting educational programs in the new material culture (Amobonye et al., 2023; Colmenero Fonseca et al., 2024).

9. Significance in the circular economy

Fungi are excellent decomposers, breaking down organic waste into organic acids, pharmaceuticals, pigments, enzymes, food products, biofuels, vitamins, amino acids, and materials for construction, packaging, and vegan leathers (Finnigan et al., 2019; Khan et al., 2024; Meyer et al., 2020; Ranghar et al., 2019). A bioeconomy aims to replace fossil and harmful processes with sustainable alternatives, utilizing renewable biomass for daily life product production (Cerimi et al., 2019). In this context, the new generation of mycelium-based functional biomaterials is aligned with the basic principles of the circular economy, promoting sustainable and efficient agricultural and forestry production using its lignocellulosic organic waste for self-harvesting. Additionally, these mycelium-based materials are based on natural polymeric compounds (chitin, cellulose, and proteins) that require minimal energy for their production and can be adjusted by modifying their nutritive substrate composition. After their useful life, these mycelium-based products can be used as sources of food for composting, fertilizers for plants, substrate for other fungi, animal feed with high nutritional value, or for obtaining new biomaterials with high nano-biotechnological value. This range of reuse makes its production more sustainable and efficient, making it suitable for various industries (Elsacker et al., 2019).

10. Conclusions

Fungi, with over 5 million species, are ideal for producing mycelium-based biomaterials due to their resilience, enzymatic capabilities, and ability to degrade complex lignocellulosic substrates. Their chitin-glucans and glycoproteins-rich cell walls provide mechanical strength, plasticity, and hydrophobicity. Mycelium, a microscopic network of filamentous cells, responds to environmental stimuli and supports nutrient flow. In controlled conditions, white rot fungi grow on lignocellulosic substrates, replacing them with fungal biomass to form lightweight, strong composites. These biomaterials have diverse industrial applications, including packaging and insulation, biotextiles, food sources, art, and architectural design. However, production technologies are still emerging, particularly in Latin America, where efforts face bioethical and technological challenges. Future research should focus on scaling up production, developing standardized protocols, and promoting regional collaboration to unlock the full potential of mycelium-based biomaterials.

CRediT authorship contribution statement

Rahim Khan: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Formal analysis, Conceptualization.

Funding

This research received no external funding.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The author acknowledges that the manuscript has undergone a thorough review before submission to the Journal.

Data availability

Data will be made available on request.

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