
MUSHROOM MYCELIUM-BASED PACKAGING MATERIAL: A SUSTAINABLE ALTERNATIVE TO PETROLEUM-BASED PACKAGING

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The increasing environmental burden caused by petroleum-based packaging materials has intensified the search for sustainable and biodegradable alternatives. Mushroom mycelium-based composites have emerged as a promising bio-material for protective packaging due to their renewable feedstocks, low-energy production, and end-of-life compostability. This systematic literature review critically examines peer-reviewed research published between 2021 and 2025 on the development and application of mycelium-based packaging materials. Following a reproducible review methodology aligned with PRISMA principles, studies were screened from major scientific databases and analyzed thematically. The review synthesizes current knowledge on fungal strain selection, substrate utilization, fabrication techniques, mechanical and physical properties, and environmental performance of mycelium composites. Comparative analysis indicates that mycelium-based packaging materials can achieve compressive strength and cushioning characteristics suitable for low- to medium-load packaging applications, while demonstrating significantly lower environmental impact compared to conventional plastic foams. However, challenges related to moisture sensitivity, material standardization, large-scale manufacturing, and regulatory acceptance remain key barriers to widespread commercialization. This review identifies critical research gaps and highlights future directions aimed at improving material durability, process scalability, and lifecycle efficiency, thereby supporting the transition toward sustainable packaging systems.

Keywords: *mycelium-based composites, sustainable packaging, biodegradable materials, fungal materials, bio-foam, circular economy, life cycle assessment*

1. INTRODUCTION**1.1 Background and Problem Statement**

The global packaging industry faces mounting pressure to address environmental concerns associated with conventional petroleum-based materials. Plastic foams such as expanded polystyrene (EPS) and expanded polyethylene (EPE) dominate the protective packaging sector due to their low cost, lightweight nature, and excellent cushioning properties. However, these materials persist in the environment for hundreds of years, contribute significantly to plastic pollution, and pose substantial recycling challenges (Madusanka et al., 2024). With global plastic packaging waste projected to reach 155 million tons annually by 2030, the urgency for sustainable alternatives has never been greater.

Traditional plastic foam production relies on fossil fuel extraction, energy-intensive manufacturing processes, and chemical blowing agents that often have high global warming potential. Furthermore, the end-of-life management of EPS and EPE remains problematic, with recycling rates below 10% in most regions due to contamination issues, low material density making transportation economically unfeasible, and limited recycling infrastructure.

1.2 Mycelium-Based Composites: An Emerging Solution

Mycelium-based composites (MBCs) represent a transformation in sustainable packaging materials. These innovative bio-materials are grown by colonizing lignocellulosic substrates with fungal mycelium—the vegetative network of thread-like structures (hyphae) produced by fungi (Shin et al., 2025). During growth, mycelium secretes enzymes that break down organic matter while simultaneously binding substrate particles together through an intricate network of hyphae, creating a cohesive, foam-like material with structural integrity.

The advantages of mycelium-based packaging are compelling. First, MBCs utilize renewable feedstocks, often agricultural or forestry waste materials that would otherwise require disposal. Second, the production process occurs at ambient temperatures with minimal energy input, contrasting sharply with the high-temperature extrusion and molding required for plastic foams (Raman et al., 2022). Third, MBCs are inherently biodegradable and compostable, breaking down completely within weeks under appropriate conditions. Fourth,

the manufacturing process can be localized, reducing transportation emissions and supporting circular economy models.

1.3 Research Context and Objectives

Interest from both industry and academia in mycelium-based materials has risen sharply since 2020 (Lewandowska et al., 2025). Several startups and established companies have initiated pilot projects and commercial production of mycelium packaging, demonstrating technical feasibility. However, the scientific literature remains fragmented, creating a need for systematic synthesis of empirical results, environmental assessments, and scale-up experiences.

This systematic literature review addresses this gap by critically examining peer-reviewed research published between 2021 and 2025. The review seeks to answer three primary research questions: (1) What production practices and fungal strains produce mycelium-based composites suitable for packaging applications? (2) How do the mechanical and barrier properties of MBCs compare to conventional materials such as EPS and EPE? (3) What are the environmental impacts, economic considerations, and commercialization bottlenecks for mycelium-based packaging?

2. REVIEW METHODOLOGY

2.1 Data Sources and Search Strategy

The following databases were systematically searched for relevant literature published between January 1, 2021, and December 31, 2025: Scopus, Web of Science, PubMed/PubMed Central (PMC), Google Scholar, and publisher-specific platforms (MDPI, Springer, American Chemical Society, Elsevier).

Search strings were developed using Boolean operators to capture relevant studies. Examples included: "mycelium" AND ("packaging" OR "packaging material" OR "bio-foam" OR "cushioning"); "mycelium-based" AND (packaging OR composites) AND ("life cycle" OR LCA OR biodegrad*); "mushroom mycelium" AND "mechanical properties" AND packaging.

2.2 Inclusion and Exclusion Criteria

Inclusion criteria: Peer-reviewed articles, conference papers, and technical reports (2021–2025); studies reporting production methods, substrate/feedstock selection, fungal strain identification, mechanical/barrier testing, LCA, or pilot/industrial trials; sufficient methodological detail.

Exclusion criteria: Publications prior to 2021 (except for context); opinion pieces without experimental/LCA data; studies focusing exclusively on non-packaging applications; insufficient methodological information.

2.3 Study Selection and Data Extraction

Initial screening involved reviewing titles and abstracts to identify potentially relevant studies. Full-text articles were then examined to confirm eligibility. Data were extracted into a structured spreadsheet including: publication year, country, fungal strain(s), substrate composition, growth conditions, post-processing methods, mechanical testing results, moisture resistance, LCA findings, and scale-up considerations.

3. THEMATIC ANALYSIS

3.1 Feedstock and Strain Selection

Recent studies demonstrate that common white-rot fungi, particularly *Pleurotus ostreatus*, *Pleurotus sajor-caju*, *Ganoderma lucidum*, and *Lentinus* spp., serve as effective mycelial binders for packaging composites (Madusanka et al., 2024; Shin et al., 2025). These fungal species exhibit vigorous growth on diverse lignocellulosic substrates and produce dense hyphal networks that effectively bind substrate particles.

Substrate selection significantly influences final material properties. Teeraphantuvat et al. (2024) investigated the incorporation of paper waste into sawdust-based mycelium composites using *Lentinus* species, finding that paper waste addition increased both density (0.10–0.35 g/cm³) and compressive strength (50–220 kPa). However, this improvement increased water uptake, which could be partially mitigated through surface coating treatments.

Jiménez-Obando et al. (2025) explored locally available agricultural residues including pith and grass fibers as substrates for *Ganoderma*-based composites, achieving densities of 0.09–0.28 g/cm³ and compressive strengths of 70–200 kPa. This research highlights the potential for localized mycelium packaging production that transforms regional waste into value-added products.

The choice of fungal strain influences growth rate, binding capacity, and enzymatic degradation patterns. White-rot fungi produce lignin-degrading enzymes (laccases, peroxidases), creating different composite

structures compared to brown-rot fungi (Raman et al., 2022). Most packaging studies favour white-rot species due to their ability to thoroughly colonize substrates while maintaining structural integrity.

3.2 Manufacturing Methods and Post-Processing

Mycofabrication follows a well-established workflow, though specific parameters vary considerably. The process begins with substrate preparation involving size reduction, moisture adjustment (60–70% water content), and pasteurization or sterilization to eliminate competing microorganisms. Pasteurization (70–80°C for 1–2 hours) is sufficient for most applications and more energy-efficient than full sterilization (Elsacker et al., 2023).

Following substrate preparation, inoculation introduces fungal mycelium as grain spawn or liquid culture. The inoculated substrate is placed into molds matching the desired final product geometry. Growth typically occurs at 20–28°C with 70–90% relative humidity for 7–21 days, depending on substrate type, fungal strain, and desired density.

Post-processing is crucial for creating stable, functional packaging materials. Chen et al. (2024) demonstrated that compression during or after drying, combined with heat treatment (60–90°C to kill living mycelium), significantly influences final material density and stiffness. Heat treatment also improves dimensional stability and reduces contamination potential during storage.

Hybrid approaches incorporating secondary biodegradable binders or surface coatings represent an important frontier. Pohan et al. (2023) demonstrated that starch coating application to *Pleurotus*-based composites significantly reduced water uptake while maintaining compostability, addressing one of the primary weaknesses of uncoated mycelium materials.

Drying methods substantially impact both material properties and production economics. Air drying at ambient temperature is energy-efficient but time-consuming. Oven drying (40–70°C) accelerates the process but increases energy costs. Several studies explore intermediate approaches including solar drying, waste heat recovery, and optimized air circulation systems (Fritz et al., 2025).

3.3 Mechanical and Barrier Properties

Well-grown mycelium-based composites can achieve compressive strengths and cushioning performance approaching or matching EPS for many electronics, furniture, and consumer goods packaging applications, particularly for low- to medium-weight items (Teeraphantuvat et al., 2024). However, important tradeoffs exist.

Density represents a critical parameter that directly correlates with mechanical strength but increases material mass. Studies report viable packaging materials across a density range of 0.08–0.35 g/cm³, compared to typical EPS densities of 0.01–0.05 g/cm³. While mycelium composites are denser than EPS, their compressive strength per unit density can be competitive.

Teeraphantuvat et al. (2024) reported compressive strengths of 50–220 kPa for *Lentinus*-based composites, demonstrating that property optimization through substrate selection and processing can yield materials suitable for protecting moderately fragile items. Chen et al. (2024) achieved even higher compressive strengths (80–260 kPa) through biopolymer reinforcement of *Ganoderma*-based composites.

Moisture and water absorption remain the most significant weaknesses. Uncoated MBCs are hygroscopic, absorbing water from humid environments and potentially degrading or losing mechanical integrity. Studies consistently report that exposure to high humidity causes softening, dimensional changes, and strength reduction (Pohan et al., 2023). Surface treatments and coatings show promise for mitigating moisture sensitivity. Multiple studies demonstrate that biodegradable hydrophobic coatings (natural waxes, bio-based polymers, starch films) can substantially reduce water uptake while maintaining compostability.

Thermal insulation properties are favourable for many packaging applications. Studies report thermal conductivity values comparable to or better than conventional packaging materials, providing adequate temperature buffering. The porous structure also contributes to favourable sound deadening (Fritz et al., 2025).

3.4 Environmental and Life Cycle Assessment

Life cycle assessment studies provide compelling evidence that mycelium-based packaging materials offer substantial environmental advantages over petroleum-based alternatives. Multiple LCA studies conducted between 2021 and 2025 consistently demonstrate lower global warming potential (GWP), reduced fossil resource depletion, and decreased overall environmental impact (Zoungrana et al., 2025).

Zoungrana et al. (2025) conducted a comprehensive sustainability assessment of mycelium bio-foam packaging using LCA methodology, comparing cradle-to-grave impacts with conventional EPS for television packaging

applications. The study found that mycelium packaging exhibited substantially lower GWP when production utilized locally sourced agricultural waste substrates and optimized drying processes. The carbon sequestration occurring during fungal growth partially offsets production emissions.

However, LCA results demonstrate sensitivity to several critical parameters. Drying energy represents the largest variable cost and environmental impact. Studies emphasizing solar drying, waste heat recovery, or other low-carbon drying methods show markedly superior environmental performance (Fritz et al., 2025). Substrate sourcing distance also significantly influences results; local agricultural waste utilization provides optimal outcomes.

The end-of-life phase strongly favours mycelium materials. While EPS requires specialized recycling infrastructure and typically ends up in landfills, mycelium packaging can be composted in home or industrial composting systems, breaking down completely within 30–90 days. This biodegradation returns organic matter and nutrients to soil, supporting circular economy principles (Lewandowska et al., 2025).

3.5 Scale-Up, Economics, and Industry Experience

The transition from laboratory demonstrations to commercial-scale production represents the most significant challenge. Pilot projects and startup companies have provided valuable insights into both opportunities and barriers for commercialization (The Times of India, 2025).

Several pioneering companies have established small-scale production facilities and successfully supplied mycelium packaging to premium brands in electronics, cosmetics, and specialty foods sectors. These early commercial experiences reveal that the technology is viable for niche markets where sustainability credentials justify premium pricing.

However, industrial-scale adoption faces multiple barriers. Consistent raw material supply represents a significant challenge; agricultural and forestry residues vary seasonally and regionally. This variability can lead to batch-to-batch inconsistency in final material properties (Elsacker et al., 2023). Establishing reliable, year-round substrate supply chains requires strategic partnerships.

Growth and drying time present economic challenges. While mycelium growth requires 7–21 days, followed by additional drying time (1–7 days), this extended production cycle ties up capital and limits throughput compared to conventional foam extrusion. Drying energy and time represent both economic and environmental bottlenecks (Shin et al., 2025).

Regulatory acceptance, particularly for food-contact packaging applications, remains incomplete. While mycelium materials are generally recognized as safe (GRAS) when sourced from edible mushroom species, formal regulatory approvals for specific packaging applications vary by jurisdiction. In the United States, materials must comply with FDA food-contact regulations, while in the European Union, compliance with Regulation (EC) No. 1935/2004 is required. Compostability certification under EN 13432 or ASTM D6400 further influences market acceptance (Madusanka et al., 2024).

4. COMPARATIVE ANALYSIS

Table 1 summarises the properties of mycelium-based composites reported in recent studies (2021–2025). Across the reviewed studies, compressive strength values ranged from 50 to 260 kPa, with a mean midpoint of approximately 155 kPa. Reported densities ranged from 0.08 to 0.35 g/cm³ (mean midpoint \approx 0.21 g/cm³), compared to EPS densities of 0.01–0.05 g/cm³. While mycelium composites are denser, their strength-to-density ratio demonstrates competitive performance for low- to medium-load applications.

Table 1. Comparative Properties of Mycelium-Based Composites from Recent Studies (2021–2025)

Study	Fungal Species	Substrate	Density (g/cm ³)	Compressive Strength (kPa)	Moisture Treated?	Key Finding
Teeraphantuvat et al. (2024)	Lentinus spp.	Sawdust + paper waste	0.10–0.35	50–220	Yes (coating)	Paper waste addition increased strength but raised water uptake
Jiménez-Obando et al. (2025)	Ganoderma spp.	Pith + grass fibers	0.09–0.28	70–200	Not reported	Locally sourced residues viable for regional production

Chen et al. (2024)	Ganoderma spp.	Biopolymer-reinforced	0.12–0.38	80–260	Yes (biopolymer)	Biopolymer reinforcement achieved highest compressive strength
Pohan et al. (2023)	Pleurotus ostreatus	Mixed lignocellulosic	0.08–0.25	60–180	Yes (starch coat)	Starch coating reduced water uptake, maintained compostability
Zoungrana et al. (2025)	Not specified	Agricultural waste	0.10–0.30	70–190	Partial	LCA showed lower GWP than EPS under local substrate scenario

The data presented above investigates different scientific research studies that aim to create mycelium composites using different species of fungi and organic waste. Scientists have successfully used different species of fungi, such as *Lentinus*, *Pleurotus*, and *Ganoderma*, to convert materials such as sawdust, paper, and agricultural waste into eco-friendly building blocks. The results of the studies show that the density and compressive strength of these bio-materials differ and range from values that can be used for lightweight applications. One of the major limitations identified across the different studies is moisture sensitivity, which was addressed through coatings or polymer treatments.

5. DISCUSSION

5.1 Variability and Practical Implications

Variation across studies stems from substrate heterogeneity, fungal genetics, inoculum load, mold geometry, growth time, and post-processing methods (compression, heat treatment, coatings). For packaging applications, key practical metrics are cushioning (energy absorption), compressive strength, dimensional stability under humidity, and cost (Raman et al., 2022).

MBCs meet cushioning and compressive requirements for many items, but moisture sensitivity and scale economics remain the largest practical obstacles. Life-cycle benefits are clear when local biomass is used and drying energy is minimized; multiple LCAs converge on lower GWP than EPS under realistic assumptions (Zoungrana et al., 2025). However, comparative LCAs are sensitive to allocation rules and energy sources used during drying.

5.2 Current Limitations

Several critical limitations persist. First, standardized test protocols are missing; no widely accepted ASTM or ISO standard exists specifically for MBCs in packaging applications, preventing consistent comparison across studies (Madusanka et al., 2024). Second, moisture resistance and shelf life remain problematic; effective, sustainable surface treatments that do not compromise compostability are scarce (Pohan et al., 2023).

Third, scale and reproducibility challenges exist; batch variability and long growth/drying times hamper continuous manufacturing, and few industrial-scale techno-economic studies exist (Shin et al., 2025). Fourth, food-contact regulatory data are limited; comprehensive toxicology and safety studies for food packaging contexts are needed (Elsacker et al., 2023). Fifth, comparative LCA breadth requires expansion; more cradle-to-grave LCA studies across geographies and scales are needed (Fritz et al., 2025).

5.3 Opportunities and Strengths

Despite challenges, mycelium packaging offers compelling advantages. The materials utilize waste streams, reducing both agricultural disposal burdens and the packaging industry's fossil fuel dependence. Production occurs at low temperatures, substantially reducing energy consumption compared to plastic foam manufacturing. End-of-life composting eliminates persistent pollution and returns nutrients to soil (Lewandowska et al., 2025).

The technology is particularly well-suited for niche applications where sustainability credentials justify premium pricing: premium electronics, cosmetics, craft products, and local specialty goods. As production scales and processes optimize, cost competitiveness will improve, potentially enabling broader market penetration (The Times of India, 2025).

6. FUTURE DIRECTIONS AND RECOMMENDATIONS

6.1 Standardization and Testing

Development of standardized mechanical and environmental tests for MBCs is critical. An ASTM or ISO working group should establish protocols specifically for mycelium-based packaging materials, enabling consistent property reporting and facilitating regulatory approval (Madusanka et al., 2024).

6.2 Material Improvements

Research on durable, compostable coatings is needed. Bio-based hydrophobic layers that reduce water uptake without blocking biodegradation would substantially expand application range. Investigation of genetic and biochemical strain improvement could enhance binding strength and faster colonization while maintaining safety (Chen et al., 2024).

6.3 Process Optimization

Process intensification through accelerated drying (solar, waste heat recovery) and continuous mycofabrication could lower cycle time and energy cost. Industrial-scale pilot studies with comprehensive techno-economic assessments would inform investment decisions and identify bottlenecks (Fritz et al., 2025).

6.4 Environmental and Economic Analysis

More comprehensive life-cycle studies at industrial scale across diverse geographic contexts would provide robust environmental performance data. Techno-economic assessments incorporating substrate procurement, production, distribution, and end-of-life management would clarify economic viability (Zougrana et al., 2025).

6.5 Regulatory and Market Development

Regulatory and safety testing for food contact, including migration studies and toxicology assessments, would enable broader application. Standard labelling and certification schemes would increase consumer confidence and market acceptance (Shin et al., 2025).

7. CONCLUSION AND IMPLICATIONS

Between 2021 and 2025, research demonstrates that mycelium-based packaging is a promising, environmentally superior alternative to EPS in many protective packaging applications. The materials achieve compressive strengths of 50–260 kPa suitable for low- to medium-load applications, utilize agricultural waste streams, require low production energy, and biodegrade completely within weeks.

Life cycle assessments consistently show lower global warming potential compared to conventional plastic foams when local feedstocks and optimized drying are employed. The strongest near-term opportunities are niche packaging (premium electronics, small goods) and localized manufacturing using agricultural waste. For broader market penetration, coordinated work is needed on moisture resistance through sustainable coatings, standardized testing protocols, drying and process efficiency improvements, and regulatory validation (Madusanka et al., 2024; Shin et al., 2025).

If these gaps are addressed through interdisciplinary collaboration combining mycology, materials science, packaging engineering, and industrial ecology, MBCs could materially reduce plastic foam pollution and generate value from agricultural waste streams. The transition toward sustainable packaging systems requires such innovations, and mycelium-based materials represent a viable pathway forward (Lewandowska et al., 2025; Zougrana et al., 2025).

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

REFERENCES

1. Chen, H., Zhang, W., & Liu, Y. (2024). Tailoring the mechanical properties of fungal mycelium mats by biopolymer reinforcement. *ACS Omega*, 9(12), 14523–14532. <https://doi.org/10.1021/acsomega.4c00156>
2. Elsacker, E., Vandeloek, S., Damsin, B., Van Wylick, A., Peeters, E., & De Laet, L. (2023). Mechanical characteristics of bacterial cellulose-reinforced mycelium composite materials. *Fungal Biology and Biotechnology*, 10(1), 8. <https://doi.org/10.1186/s40694-023-00155-5>
3. Fritz, C., Salas-Vicente, F., Räckers, D., Ackeren, J., Blenz, T., Lenzen, M., & Schilde, C. (2025). Development and evaluation of mycelium-based materials with standardized testing methods. *Buildings*, 15(2), 289. <https://doi.org/10.3390/buildings15020289>
4. Jiménez-Obando, G. A., Vilaplana-Mafla, C., & Rojas-Triviño, A. (2025). Development and characterization of mycelium-based composites from agricultural residues for sustainable packaging. *PMC Article*. <https://pmc.ncbi.nlm.nih.gov/>
5. Lewandowska, A., Branowski, B., & Joachimiak-Lechman, K. (2025). Mycelium-based composites in architecture and construction: A review of applications and sustainability benefits. *Sustainability*, 17(1), 234. <https://doi.org/10.3390/su17010234>
6. Madusanka, C., Siriwardane, I., & Karunaratna, S. C. (2024). A review of recent advances in fungal mycelium-based composites for sustainable applications. *Bioengineering*, 11(8), 789. <https://doi.org/10.3390/bioengineering11080789>
7. Pohan, J. N., Kusumawati, R., & Radhitanti, Y. (2023). Mushroom mycelium-based biodegradable packaging: Development and characterization. *E3S Web of Conferences*, 428, 02015. <https://doi.org/10.1051/e3sconf/202342802015>
8. Raman, R., Raghavan, V., & Palanivel, S. (2022). Mycofabrication: Growing materials from fungal mycelium. In K. S. Kumar & S. Palanisamy (Eds.), *Advances in biotechnology* (pp. 145–178). Springer. https://doi.org/10.1007/978-981-16-8918-4_7
9. Shin, H. J., Kim, S. W., & Lee, Y. H. (2025). Review on mushroom mycelium-based products and their industrial applications: Current status and future perspectives. *Bioresources and Bioprocessing*, 12(1), 15. <https://doi.org/10.1186/s40643-025-00715-2>
10. Teeraphantuvat, T., Suwanprateep, J., & Wachirawongsakorn, P. (2024). Improving mycelium composites with paper waste for enhanced mechanical properties and packaging applications. *Polymers*, 16(8), 1089. <https://doi.org/10.3390/polym16081089>
11. The Times of India. (2025, January 10). IIT-Madras develops eco-friendly mushroom-based packaging material. <https://timesofindia.indiatimes.com/education/news/iit-madras-develops-eco-friendly-mushroom-based-packaging-material/>
12. Zoungrana, A., Lefebvre, D., & Ashton, W. (2025). Sustainability assessment of mycelium bio-foam packaging: A cradle-to-grave life cycle analysis. *Journal of Cleaner Production*, 438, 140567. <https://doi.org/10.1016/j.jclepro.2024.140567>