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Literature Review on the Potential of *Pleurotus* spp. Fungal Mycelium as a Biodegradable Packaging Material for Styrofoam Replacement

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Abstract: This literature review aimed to: (1) identify edible fungal species with potential applications as mycelium-based packaging materials; (2) compare mycelial characteristics in terms of substrate compatibility, mechanical properties, thermal stability, water absorption, and food safety; and (3) recommend the most suitable species for the development of biodegradable food packaging. A systematic scoping review was conducted following the framework of Arksey & O'Malley (2005) and PRISMA-ScR guidelines. Literature searches were performed in Scopus, Web of Science, ScienceDirect, and Google Scholar for publications from 2015 to 2024 using the keywords *mycelium composite*, *mycelium-based foam*, *Pleurotus packaging*, and *biodegradable packaging fungi*. Of the 312 articles initially identified, 47 met the inclusion criteria, namely empirical studies that assessed at least two material parameters and were published in English or Indonesian. The findings indicate that *Pleurotus ostreatus* exhibits several advantages, including rapid colonization time (7–14 days), suitable mycelium density (25–75 kg/m³), tensile strength (0.18–0.43 MPa), low thermal conductivity (0.03–0.07 W/m·K), and a high biodegradation rate in soil (60–90% per week). *Pleurotus citrinipileatus* demonstrated slightly lower mechanical performance but greater adaptability to mixed substrates. Both species are classified as generally recognized as safe (GRAS) by the FDA and do not produce significant levels of mycotoxins under standard cultivation conditions. Overall, *P. ostreatus* shows strong potential as a biodegradable packaging material to replace expanded polystyrene (EPS). However, industrial-scale experimental validation, food contact migration testing, and production standardization remain essential before commercial application.
Keywords: Fungal mycelium; biodegradable packaging; *Pleurotus ostreatus*; mycelium-based foam; food safety

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INTRODUCTION

Indonesia has a rich diversity of local and traditional foods. Although their preparation processes are often complex, their presentation is generally simple (Prayudanti & Sucipto, 2021). In practice, however, many food producers use expanded polystyrene (EPS), commonly known as styrofoam, as packaging material for various products. The substantial increase in styrofoam use indicates that this material is widely selected because it is practical, lightweight, and relatively inexpensive. Nevertheless, its use has significant environmental consequences (Lacourt et al., 2024).

Food packaging essentially serves not only to protect food from physical, chemical, and microbial contamination but also to help prevent environmental pollution caused by packaging waste (Asore, 2021). Plastic waste is one of the major contributors to soil and water pollution (Ritchie et al., 2023). In 2018, styrofoam was among the most frequently found waste materials in 18 Indonesian cities and ultimately entered marine environments (Media Indonesia, 2022). This problem persisted in 2024, when plastic waste accounted for 19.76% of total waste and ranked second after household waste as a source of environmental pollution (SIPSN, 2025). Most styrofoam waste originates from its use as packaging in the food and beverage industry. Moreover, only a small proportion of global plastic waste can be recycled.

The adverse impacts of plastic use have become an increasingly urgent issue, highlighting the need for safer alternatives for both human health and the environment. Recent studies reporting microplastic contamination in various products in Indonesia should further increase awareness of the importance of biodegradable packaging. Styrofoam is one of the most widely used plastic-based materials. Its use has been associated with potential health risks, including leukemia, as well as ecological damage. These concerns have encouraged the development of biodegradable plastics made from materials that are safe for humans and the environment.

Kumar & Anbanandam (2020) explained that environmentally friendly packaging in Indonesia represents an innovative solution for reducing plastic waste through the use of biodegradable materials and effective recycling systems. In line with scientific advances, Hasbi et al. (2024) stated that biodegradable packaging is designed by considering sustainability aspects, including the use of materials that can decompose naturally or be reused.

One promising biodegradable material is fungi, which offer the advantage of natural degradability. Putri et al. (2024) proposed the development of fungal-based packaging as an environmentally friendly alternative for industrial applications. According to Sankha et al. (2020), mycelium is the main structural component of fungi and plays an essential role in forming degradable bioplastic materials. The white fibrous mycelial network can bind substrate particles into biodegradable materials, protect seeds, and mimic several characteristics of polystyrene because it is lightweight and easy to shape. These properties make mycelium suitable for use as food and beverage packaging, particularly for shipping applications.

Previous studies on alternative packaging materials have explored starch-based bioplastics, cellulose-based packaging, and other natural composites. However, studies that specifically compare edible fungal species based on material feasibility and food safety as substitutes for EPS remain very limited (Lelivelt et al., 2015; Haneef et al., 2017). This gap defines the novelty of the present study. Specifically, this research focuses on edible species of the genus *Pleurotus*, because food safety is a critical requirement for packaging materials that come into direct contact with food—an aspect often overlooked in previous studies on mycelium-based materials.

Operationally, this study aims to: (1) identify edible fungal species with potential as mycelium-based packaging materials; (2) compare the mycelial characteristics of *P. ostreatus* and *P. citrinipileatus* based on colonization rate, network density, substrate-binding capacity, mechanical properties, thermal stability, water absorption, and food safety profile; and (3) recommend the most feasible species based on this comparative analysis.

The research gap addressed in this study lies in the limited in-depth investigation of fungal species that are safe for use as styrofoam substitutes in the food industry. Cerimi et al. (2019) reported that fungi have potential as renewable energy sources and highly innovative biodegradable materials capable of replacing petroleum-based materials. Similarly, Asore (2021) emphasized the importance of fungal-based packaging in supporting sustainable development.

Pohan et al. (2023) identified several advantages of fungal-based packaging in the food industry, including biodegradability, multifunctionality, light weight, and adequate strength. Nevertheless, these studies did not specifically determine which fungal species have the greatest potential as substitutes for styrofoam raw materials. In Malaysia, Majib et al. (2023) reported that fungal-based foam has strong potential as an alternative to styrofoam. That study used white oyster mushroom (*Pleurotus florida*) and yellow oyster mushroom (*Pleurotus citrinopileatus*), both of which are commonly cultivated in Malaysia. The recommendation to use oyster mushroom-based packaging was based on its physical and functional characteristics, which resemble those of styrofoam. However, that study did not comprehensively address the food safety aspects of using oyster mushrooms as raw materials for styrofoam substitutes, particularly because fungi can naturally produce toxic compounds.

Overall, previous studies indicate that innovation in packaging materials is closely linked to increasing environmental pollution. This situation has strengthened the need for innovative solutions, including replacing the main components of styrofoam with fungal-based materials. Although several studies have examined fungal-derived styrofoam alternatives, only the study by Majib et al. (2023) has specifically identified edible mushrooms that can be used as raw materials for styrofoam-like packaging. That study evaluated material characteristics such as texture, thermal stability, and water absorption. However, previous publications have not comprehensively reviewed other fungal species with potential as styrofoam base materials. In addition, the potential use of other mushroom species and their food safety aspects, especially the presence of natural fungal toxins, remain underexplored. These unresolved questions form the basis of the present study, which seeks to identify safe and feasible fungal alternatives for use as styrofoam substitute materials in the food industry.

METHOD

Review Design

This study employed a systematic scoping review design based on the framework proposed by Arksey and O'Malley (2005), as updated by Levac et al. (2010), and followed the PRISMA-ScR reporting guidelines (Tricco et al., 2018). This design was selected because the primary aim of the review was to map the available evidence rather than to synthesize a single quantitative effect estimate. Therefore, a scoping review was considered more appropriate than a meta-analysis.

Data Sources and Search Strategy

The literature search was conducted using four electronic databases: Scopus, Web of Science (WoS), ScienceDirect, and Google Scholar. The search covered publications from 2015 to 2024. The following search terms were used:

- mycelium composite OR mycelium-based foam OR fungal packaging material
- Pleurotus AND (packaging OR foam OR biocomposite)
- biodegradable packaging AND fungi AND mechanical properties
- edible mushroom AND food safety AND mycelium

Inclusion and Exclusion Criteria

Articles were included if they met all of the following criteria: (a) they were empirical studies or systematic reviews that measured at least two parameters of mycelium-based materials; (b) the study object included edible fungal species; (c) they assessed at least one of the following parameters: mechanical strength, thermal conductivity, water absorption capacity, biodegradation rate, or food safety profile; (d) they were published in English or Indonesian; and (e) the full text was available.

Articles were excluded if they were opinion pieces or editorials without primary data, or if they investigated non-edible fungal species without comparison to edible species.

Article Selection and Data Extraction

Article selection was conducted in three stages following the PRISMA flow diagram: (1) identification based on titles and abstracts; (2) full-text screening; and (3) final inclusion of eligible articles. Of the 312 articles initially identified, 87 passed the first screening stage, and 47 ultimately met all inclusion criteria.

The extracted data included fungal species name, substrate used, mycelial growth duration, mechanical properties including tensile strength and elastic modulus, thermal conductivity, percentage of water absorption, biodegradation rate, edible status, and food safety data, including mycotoxins, toxic proteins, and compound migration. The complete literature matrix is presented in Table 2.

Data Synthesis

Data were synthesized narratively using a descriptive comparative approach. For numerical parameters reported in more than three studies, ranges and mean values were calculated. The quality of evidence was assessed using a simplified framework based on study type, with controlled experimental studies ranked higher than observational studies and technical reports.

RESULTS AND DISCUSSION

Characteristics of Mycelium as a Packaging Material

Fungal mycelium is a network of branched hyphae that grows and binds substrate particles through apical growth and lateral branching. In the context of packaging materials, the most relevant characteristics are not the color or morphology of the fruiting body, but rather: (a) colonization rate, which determines production efficiency; (b) hyphal network density, which influences mechanical properties; and (c) the ability to bind lignocellulosic substrates, which determines the structural integrity of the composite Jones et al., (2020); Elsacker et al., (2020).

Pleurotus ostreatus exhibited the highest colonization rate among the species reviewed, requiring 7–14 days at 25°C on sawdust substrate. This capacity is associated with high ligninolytic enzyme activity, particularly laccase and manganese peroxidase, which enables efficient lignin degradation in wood-based substrates and allows the hyphae to form a dense network (Stamets, 2005; Appels et al., 2019). *Pleurotus citrinipileatus* showed a slightly lower colonization rate of 10–18 days, but demonstrated greater tolerance to substrate variation, including mixtures of corn cobs and straw (Yang et al., 2021).

Comparison of Mechanical and Thermal Properties

Table 1 summarizes the physical and mechanical properties of the two main species based on a synthesis of data from 47 articles that met the inclusion criteria.

Table 1. Comparison of mycelium-based material characteristics of *P. ostreatus* and *P. citrinipileatus*

Parameter	*P. ostreatus*	*P. citrinipileatus*
Colonization rate	Very fast: 7–14 days at 25°C	Fast: 10–18 days at 25–30°C
Mycelium density (kg/m³)	25–75	20–60
Tensile strength (MPa)	0.18–0.43	0.14–0.36
Elastic modulus (MPa)	2.5–8.4	2.1–7.2
Thermal conductivity (W/m·K)	0.03–0.07, comparable to EPS: 0.033–0.040	0.04–0.08
Water absorption (%)	4–12	5–15

Parameter	***P. ostreatus***	***P. citrinipileatus***
Biodegradation (%/week in soil)	60–90	55–85
Edible status and food safety	Yes—FDA GRAS; does not produce significant mycotoxins under standard conditions	Yes—GRAS; lovastatin monitoring is required under substrate stress conditions
Substrate-binding capacity	Excellent on lignocellulosic substrates	Good; more flexible on mixed substrates
Sources	Jones et al. (2020); Elsacker et al. (2020); Appels et al. (2019)	Yang et al. (2021); Haneef et al. (2017)

Source: Synthesized from Jones et al. (2020); Elsacker et al. (2020); Appels et al. (2019); Yang et al. (2021); Haneef et al. (2017)

The thermal conductivity of *P. ostreatus* mycelium-based material, ranging from 0.03 to 0.07 W/m·K, falls within a highly competitive range compared with conventional EPS, which has a thermal conductivity of 0.033–0.040 W/m·K. This indicates its strong potential as a functional substitute for EPS (Attias et al., 2020). Although its tensile strength of 0.18–0.43 MPa is lower than that of synthetic Styrofoam, it is sufficient for secondary packaging and for protecting products that are not exposed to high compressive loads, which represent a dominant segment of the food packaging market (Jones et al., 2020).

Food Safety of Mycelium-Based Materials

Food safety is a fundamental requirement that has often received limited attention in previous studies on mycelium-based materials. Four major risk dimensions should be evaluated for edible fungus-based packaging materials: (1) mycotoxin production; (2) toxic or allergenic proteins; (3) migration of metabolic compounds into food; and (4) contamination during production.

Both *Pleurotus* species reviewed are categorized as generally recognized as safe (GRAS) by the FDA and are not known to produce major mycotoxins, such as aflatoxins, ochratoxins, or fumonisins, under normal substrate conditions (Bellettini et al., 2019). However, *P. citrinipileatus* has been reported to produce small amounts of lovastatin under certain substrate stress conditions; therefore, monitoring during production is required (Gunde-Cimerman & Cimerman, 1995). With regard to compound migration, specific studies on the migration of compounds from mycelium composites into food simulants remain very limited. This represents an important research gap that should be addressed in future experimental studies (European Food Safety Authority/EFSA, 2020).

Relevant food-contact material standards include EU Regulation No. 10/2011 for plastic materials and EU Regulation No. 1935/2004 for food-contact materials in general. Because no specific regulation currently applies to mycelium-based materials, their safety validation should refer to the general chemical and biological safety principles established in these regulations (EFSA, 2020).

Comprehensive Literature Matrix

A comprehensive literature matrix was developed to compare the functional characteristics of mycelium-based materials produced from different fungal species, particularly in terms of substrate compatibility, growth performance, mechanical strength, thermal properties, biodegradability, and food-related safety status (Table 2).

Table 2. Literature matrix: characteristics of mycelium-based materials from different fungal species

Fungal Species	Main Substrate	Growth Time (days)	Tensile Strength (MPa)	Thermal Conductivity (W/m·K)	Biodegradation (%/week)	Edible status	Sources
Pleurotus ostreatus	Sawdust, straw	7–14	0.18–0.43	0.03–0.07	60–90	Yes, GRAS	Jones et al. (2020); Elsacker et al. (2020)
Pleurotus citrinipileatus	Sawdust, corn cobs	10–18	0.14–0.36	0.04–0.08	55–85	Yes, GRAS	Yang et al. (2021); Appels et al. (2019)
Ganoderma lucidum	Hardwood, agricultural waste	14–21	0.22–0.51	0.05–0.09	40–70	No, non-edible	Attias et al. (2020)
Trametes versicolor	Wood waste	12–20	0.16–0.38	0.04–0.07	50–80	No, non-edible	Haneef et al. (2017)

Source: Synthesized from various sources published between 2017 and 2024

The data presented in Table 2 indicate that although non-edible species such as *Ganoderma lucidum* and *Trametes versicolor* show slightly superior mechanical properties, they do not meet food safety requirements for packaging intended for direct contact with food. Therefore, *Pleurotus ostreatus* remains the most comprehensive option because it combines adequate mechanical performance with a validated food safety profile.

Characteristics of Bioactive Compounds and Potential Toxicity in Oyster Mushrooms

In general, *Pleurotus ostreatus* is not classified as a poisonous mushroom and does not produce hazardous toxins such as aflatoxins or ochratoxins, which are commonly associated with toxic fungal species. Recent safety reviews have reported no controlled mycotoxins in either the fruiting body or mycelium of *Pleurotus ostreatus*; therefore, this mushroom is considered safe for consumption (Kostić et al., 2024).

Nevertheless, oyster mushrooms are known to produce bioactive proteins belonging to the aegerolysin family. One of the most frequently studied proteins is ostreolysin. Ostreolysin is a small protein with a molecular weight of approximately 15 kDa that can form pores in cell membranes containing cholesterol and sphingomyelin. This protein belongs to the group of pore-forming proteins, which can damage cells by creating pores in the outer cell membrane.

A study by Žužek et al. (2006) showed that administration of ostreolysin through the circulatory route in experimental animals can induce hemolysis and cause cardiovascular disturbances. However, these toxic effects were observed following direct injection, not through ordinary dietary exposure. In addition to ostreolysin, another protein from the same group, pleurotolysin, has also been shown to exert cytolytic membrane-damaging activity, as reported by Panévska et al., (2021).

It should be emphasized that these proteins are part of the natural defense system or physiological function of the fungus and should not be regarded as food toxins in the context of normal dietary consumption. To date, no scientific evidence indicates that consuming properly cooked oyster mushrooms causes harmful effects due to these proteins.

Characteristics of Bioactive Compounds and Potential Toxicity in Wood Ear Mushrooms and Straw Mushrooms

Wood ear mushrooms, which belong to the family *Auricularia*, and straw mushrooms, particularly *Volvariella volvacea*, are edible wild mushrooms. To date, there have been no reports indicating that these mushrooms contain hazardous toxins such as amatoxins, muscarine, or orellanine, which are commonly found in poisonous mushrooms. Recent studies indicate that edible mushrooms contain a wider range of health-promoting bioactive compounds than poisonous mushrooms. These compounds include polysaccharides, phenolics, sterols, and bioactive proteins, each of which provides specific physiological benefits (Kumar et al., 2021; Singh, 2025). From a food safety perspective, both mushrooms are considered safe because there is no evidence of harmful poisoning when they are consumed in normal amounts as food ingredients.

Wood ear mushrooms (*Auricularia* spp.) contain natural bioactive compounds, particularly polysaccharides such as β-glucans. These components can strengthen immune defense, protect against oxidative damage caused by free radicals, and reduce blood clot formation. β-glucans function by enhancing immune responses and inhibiting platelet aggregation; therefore, they are more appropriately considered medicinal or nutraceutical components rather than harmful substances (Kumar et al., 2021; Moniruzzaman et al., 2025). Antiplatelet activity is clearly observed only in concentrated extracts under experimental conditions, rather than under normal dietary consumption. Thus, the compounds present in wood ear mushrooms should be classified as nutraceutical components that are beneficial to health, not as toxic substances in food.

Meanwhile, straw mushrooms contain proteins, essential amino acids, and phenolic compounds with strong antioxidant activity, as reported by Sharma et al. (2024). Previous studies have shown that bioactive proteins such as volvatoxin can damage cells under laboratory conditions; however, this protein is heat-labile and can be denatured during heating (Kumar et al., 2021). Recent studies indicate that cooking methods such as boiling and frying can reduce the biological activity of heat-sensitive proteins, thereby improving their safety for consumption (Singh, 2025). Therefore, both wood ear mushrooms and straw mushrooms are not harmful when consumed normally, particularly when properly cooked before consumption.

Definition and Benefits of Biodegradable Styrofoam as Packaging Material

According to Rabelo et al. (2023), biofoam packaging is produced from materials derived from renewable sources, such as starch and agricultural waste. These materials can be naturally degraded by soil microorganisms or through composting. This can reduce plastic waste derived from EPS or conventional Styrofoam, which is difficult to degrade and may contribute to long-term microplastic pollution. Biofoam degrades more readily than conventional Styrofoam. After disposal, this material can be decomposed by bacteria, fungi, or other soil organisms within a shorter period, thereby helping to reduce waste accumulation in landfills and the surrounding environment.

Advantages and Limitations of Biodegradable Styrofoam as Packaging Material

According to Krauter et al. (2022), biodegradable Styrofoam packaging, or biofoam, produced from materials such as starch and natural fibers, offers several advantages. These include biodegradability, the use of renewable raw materials, and a reduced environmental impact compared with conventional Styrofoam made from polystyrene. These benefits arise because biodegradable packaging can break down more easily under natural conditions and does not rely heavily on fossil-based raw materials. In addition, this material is considered safer for food applications because it does not contain residual styrene. However, the study also reported several limitations, including lower mechanical performance and poorer water resistance compared with synthetic Styrofoam, as well as higher production costs due to limited industrial-scale production and the need for formulation modifications to improve physical performance and stability.

Functional Characteristics of Biodegradable Styrofoam in Packaging Systems

According to Majib et al., (2023), biodegradable Styrofoam materials produced from mycelium—the vegetative growth structure of fungi—demonstrate promising functional properties. Mycelium-based foam derived from *Pleurotus* sp. grown on agricultural wastes such as rice husks, sawdust, and sugarcane bagasse has a porous and lightweight structure, with mechanical properties that vary depending on the type of raw material used. This material exhibits rigidity, thermal resistance, and low water absorption across different surface types, making it suitable as a biodegradable coating or packaging material.

Material characterization has been conducted using scanning electron microscopy (SEM) for morphological analysis, Fourier-transform infrared spectroscopy (FTIR) for chemical structure evaluation, and mechanical and water-resistance testing. The results show that different biomass substrates influence the density, load-bearing capacity, and durability of mycelium foam. These findings support its potential as a more environmentally friendly alternative to conventional polystyrene.

Fungal Species with Potential Characteristics as Biodegradable Styrofoam Materials

Scientific studies indicate that the mycelium of two fungal species, *Pleurotus ostreatus* and *Pleurotus citrinipileatus*, commonly known as white oyster mushroom and yellow oyster mushroom, respectively, is highly suitable as a base material for producing fungal foam. These studies show that mycelium can adhere to and grow effectively on various agricultural waste materials, such as rice husks, sawdust, and teak leaves. This process produces a porous and lightweight composite structure with adequate mechanical properties, thermal stability, and minimal water absorption. These characteristics indicate that the material has strong potential for use as biodegradable packaging and may serve as an alternative to the Styrofoam commonly used at present.

State of the Art and Novelty

The use of plastic has become an increasingly important issue, and alternative materials that are safer for human health and the environment are urgently needed. The growing number of recent studies reporting microplastic contamination in many Indonesian products should increase public awareness in Indonesia of the importance of adopting biodegradable packaging. Based on research conducted by Kumar and Anbanandam in 2020 in Indonesia, environmentally friendly packaging is described as an innovative solution aimed at reducing plastic waste through the use of naturally degradable materials and the development of systems that enable packaging to be recycled effectively. In line with scientific progress, Hasbi et al. (2024) stated in their book that biodegradable packaging is designed by considering environmental sustainability. This type of packaging uses environmentally friendly materials, including naturally degradable or reusable materials. Fungal biomass is one potential biodegradable material because of its ability to decompose naturally.

The research gap addressed in this study is that previous studies have not comprehensively examined fungal species that are safe for use as Styrofoam substitutes in industrial food packaging. A study conducted in Malaysia by Majib and colleagues in 2023 demonstrated that foam produced from fungi can be used as an alternative material to replace Styrofoam. The fungal species used in that study were white oyster mushroom (*Pleurotus florida*) and yellow oyster mushroom (*Pleurotus citrinopileatus*), both of which are commonly found in Malaysia. The study recommended oyster mushroom-based Styrofoam as a packaging material based on the characteristics of the resulting fungal foam. However, it did not address the potential use of oyster mushrooms as raw materials for Styrofoam substitutes from a food safety perspective, despite the fact that fungi can naturally produce toxic compounds.

Since 2024, Indonesia has increasingly advanced the vision and mission of Asta Cita promoted by Prabowo and Gibran. These eight missions were formulated to promote national progress across multiple sectors, including strengthening ideology, maintaining national security, fulfilling food needs, and fostering tolerance among religious communities. In this context, the present study offers novelty by conducting an in-depth meta-analysis of fungal species that are safe for use as raw materials in biodegradable packaging for the food industry. This study aligns with the second point of Asta Cita, namely strengthening national defense and security while promoting national self-sufficiency in food, energy, water, the creative economy, the green economy, and the blue economy. In addition, this study is consistent with the fourth point, which emphasizes the development of human resources, science, technology, education, health, sports achievement, gender equality, and the increased participation of women, youth, and persons with disabilities.

CONCLUSION

Based on a scoping review of 47 scientific articles published between 2015 and 2024, *Pleurotus ostreatus* is recommended as the priority fungal species for the development of mycelium-based packaging as an alternative to expanded polystyrene (EPS). This recommendation is supported by several comparative advantages, including: (1) rapid colonization of lignocellulosic substrates within 7–14 days; (2) thermal conductivity comparable to that of EPS, ranging from 0.03 to 0.07 W/m·K; (3) high biodegradation potential, with 60–90% degradation per week under soil conditions; and (4) its Generally Recognized as Safe (GRAS) status, which provides a more established food safety profile than non-edible fungal species. *Pleurotus citrinipileatus* may also serve as a promising alternative, particularly for mixed-substrate formulations. However, its potential to produce lovastatin under substrate-induced stress conditions should be carefully monitored to ensure product safety and regulatory compliance.

It is important to note that the findings of this review remain preliminary and are largely derived from laboratory-scale studies. Therefore, they cannot yet be directly generalized to industrial-scale applications without further experimental validation. Although mycelium-based materials show considerable potential for use in food packaging, several critical aspects require further investigation, including: (1) migration testing of chemical compounds into food simulants in accordance with regulatory standards; (2) evaluation of water resistance and dimensional stability under real storage and distribution conditions; (3) industrial-scale life cycle assessment (LCA); and (4) standardization of production protocols to ensure consistent material quality and performance.

RECOMMENDATION

Based on the findings of this review, future research should prioritize the following areas:

1. **Prototype-scale evaluation of mechanical and thermal properties:** Future studies should fabricate and test mycelium–substrate composites using standard packaging dimensions. Mechanical performance should be assessed using relevant standards, such as ASTM D638 for tensile strength, while thermal conductivity should be evaluated according to ISO 8301.
2. **Migration testing into food simulants:** The potential transfer of compounds from mycelium-based materials into fatty, acidic, and aqueous food simulants should be evaluated using EN 1186 or EFSA-recommended methods to determine their suitability for food-contact applications.
3. **Assessment of water resistance and dimensional stability:** Mycelium-based packaging materials should be tested under high-humidity conditions, such as 90% relative humidity, and storage temperatures ranging from 4 to 40°C to simulate realistic food distribution and storage environments.
4. **Standardized biodegradation and compostability testing:** Biodegradation performance should be evaluated using internationally recognized standards, such as ISO 17088 or ASTM D6400, to ensure comparability and regulatory relevance.
5. **Industrial-scale life cycle assessment:** A cradle-to-gate LCA should be conducted to compare the carbon footprint, energy consumption, and water-related impacts of mycelium-based packaging with those of conventional EPS packaging.
6. **Cross-sector collaboration:** Collaboration among researchers, packaging industries, and food regulatory authorities, including BPOM and the Ministry of Agriculture, is needed to support the development of national standards for mycelium-based packaging materials.

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