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ABSTRACT

In transitioning toward a sustainable economy, mycelial materials are recognized for their adaptability, biocompatibility, and eco-friendliness. This paper updates the exploration of mycelial materials, defining their scope and emphasizing the need for precise terminology. It discusses the importance of mycelial type and characteristics, reviews existing and future research directions, and highlights the need for improved understanding, clarity, and standardization in this emerging field, aiming to foster and guide future research and development in sustainable material science.

I. INTRODUCTION

With the rapid pace of economic growth leading to significant resource depletion, there is a growing necessity to reorient industrial practices toward sustainability. This urgency is reflected in the field of material science, giving rise to the development of eco-friendly materials.[1] Among these, mycelial materials stand out for their adaptability, biocompatibility, and eco-friendliness. These unique characteristics position mycelial materials as a promising solution in the quest for environmentally friendly alternatives to traditional materials.[2]

Mycelia, the vegetative root-like structure of fungi, naturally produces intricate networks of interconnected thread-like fungal cells.[3] Harnessing the remarkable ability of wood-degrading fungi to penetrate and break down lignocellulosic biomass,[4] researchers have employed them as a unique bio-adhesive to bind lignocellulosic substrates producing foam-like and panel-like structures for packaging, insulation, and construction applications.[5] The intricacies of the entangled pure mycelium structure have generated innovations such as leather substitutes,[6] filtration membranes,[7] and wound healing devices.[8] Recent innovative efforts have also been able to cultivate mycelia within diverse materials such as textiles,[9] hydrogels,[10] and food waste,[11] highlighting the adaptability of mycelia to form a range of material properties. This adaptability opens doors to a variety of forms and properties for materials incorporating fungal mycelial elements. A wide range of both conventional and avant-garde techniques has been applied to explore and utilize the potential of mycelial materials, from mold-based cultivation to additive manufacturing,[10] indirect cultivation,[12] and continuous filmmaking.[13] This versatility has also extended to more advanced applications, such as off-earth construction,[14] biomedical devices,[15] and sensors,[16] offering a clear insight into the extensive scope of their potential.

New techniques are continually evolving from research projects and industrial developments. Enhancing communication and collaboration across various fields and fostering connections between academia and industry, along with wider community involvement, is crucial for the development of these materials. Among the key challenges is the need for improved understanding, clarity, and standardization. This paper aims to present an updated overview of mycelial materials, focusing on key elements considering the latest advancements. Its objective is to investigate potential opportunities and challenges, providing insights into areas needing enhancement. Ultimately, it seeks to direct progress in a well-informed and strategic way.

II. SCOPE, NOMENCLATURE, AND CLASSIFICATION

Precisely defining the scope of mycelial materials is crucial for encouraging productive discussions and collaborations in this field. Mycelium, the vegetative part of fungi, is central to this category, giving mycelial materials their unique characteristics. While fungi have been integral to material development for centuries, evident in uses ranging from fermentation in the food industry[17] to biofuel and chemical compound production field,[18] the focus on mycelial materials as a specialized field is a more recent development.

The term "mycelial material" highlights the vital role of fungal mycelia in these materials. In this context, mycelia should either be the primary constituent, as seen in pure mycelial products, or play an indispensable role, such as binding all other elements together in composite structures. To qualify as a mycelial material, the mycelial component should also define the primary structural or chemical characteristics of the final product. Microscopically, this involves the assembly of fine, thread-like structures of fungal hyphae.[3] Chemically, these hyphae are distinguished by a unique multi-lamellar structure. This structure comprises highly branched chitin linked with alkali-insoluble beta-glucans at its core, surrounded by a complex outer layer of proteinaceous, alkali-soluble glucans, and glycoproteins.[19]

Thus, labeling a product that lacks the thread-like hyphae network or most of the chemical components as "mycelial material" would be misleading. More precise terms, such as "mycelium-derived" or "fungal-derived" materials, should be used for materials extracted from mycelia or other parts of fungi. Examples of such materials include polysaccharides such as chitin[20] and exopolysaccharides[21] and proteins such as hydrophobin[22] extracted from mycelia or other fungal parts. This approach to nomenclature is similar to the practices established in the pulp and paper industry. "Pulp" refers specifically to the broken-down fibers, primarily from lignocellulosic sources.[23] When they undergo further processing, they yield products of different sizes with different names, such as cellulose nanofibrils and cellulose nanocrystals.[24] Labeling a product made primarily of nanocellulose as a "pulp film" would not accurately reflect its composition or characteristics.

Currently, the emerging field of mycelial materials lacks a standardized nomenclature. In many instances, much literature[25–29] erroneously uses "mycelium-based" to describe mycelium-bound composite materials. This mislabeling can lead to confusion as in those composites, mycelia only account for a small amount. According to the Cambridge Dictionary, "-based" is used to form adjectives describing the main substance or object from which a particular substance is made.[30] Therefore, "mycelium-based composites" should specifically refer to materials predominantly composed of mycelia, such as films made of mycelia with a minimal addition of other substances.[31] In the case of hot-pressed, higher-density panels where mycelia contribute significantly to the structural integrity through adhesion, the term "mycelium-bonded composites" is more appropriate.[32]

This lack of standardized terminology poses a challenge in the field, with only one very recent paper proposing a classification system.[33] Therefore, this paper proposed a classification system for mycelial materials, categorizing them based on their distinctive features and the typical products they contribute to, aiming to further contribute to the standardization of terminology in this emerging field. This classification system, as illustrated in Fig. 1, is based on fungal mycelia as the essential material. Through various processing techniques, a diverse range of products is produced. In the case of mycelium-bound composites, depending on their density, they can be further classified into categories such as mycelium-bound foam and mycelium-bonded panel. For products predominantly made of mycelium, known as pure mycelium-based products, they resemble other fiber-assembled materials and include lower-density items like foam or aerogel, as well as sheet-like products such as leather, film, or membrane. Composites created through additive manufacturing processes are categorized distinctly within the mycelium-bound composite group. These often involve a secondary growth phase of mycelia post-3D printing, leading to their occasional reference as 4D printed composites.

III. ARE THEY A KIND OF NEW MATERIAL/PRODUCT?

Mycelia have long played a crucial role in natural ecosystems, predominantly serving their ecological role as decomposers.[34] It is only in recent times that their potential as viable materials has been explored, introducing them as a novel category in material science. A unique characteristic of mycelia is their classification as living organisms, which can be engineered to interact with non-living materials and respond to environmental stimuli predictably.[35]

It is important to recognize that in academic literature, the term "material" often extends beyond the substance of an object. While raw mycelia may be considered innovative, the products produced from them typically align with existing material paradigms. Many mycelium-related innovations, whether under research or already commercialized, parallel established market products, particularly in sectors such as thermal insulation, packaging, and leather substitutes. However, the key innovation of these products often lies more in their sustainability and low-carbon attributes. Therefore, it is crucial to compare these mycelial products with their traditional counterparts to ensure they meet the necessary standards for their intended applications. A concerning trend in contemporary research is the inclination to highlight the novelty of mycelial materials, showcasing specific exemplary traits while overlooking other critical attributes. This approach often emphasizes the material's innovation without fully addressing the familiarity of the end product and its well-established applications.

Table I provides a detailed comparison between selected mycelial products and their commercial counterparts. In the sector of mycelium-bound composites, for instance, mycelium-bound foams and mycelium-bonded panels are compared to expanded polystyrene and particleboards, respectively. To be considered viable replacements, these mycelial composites must demonstrate equivalent or superior properties compared to their traditional counterparts. Their mechanical strength is commendable, mycelium-bound foams exhibit compressive strengths that exceed those of synthetic foams[36, 37] and mycelium-bonded panels possess modulus of rupture values that meet the standards for particleboards.[5, 32] However, notable differences are also present. For instance, mycelium-bound foams typically have higher densities than standard synthetic foams,[36, 38] and mycelium-bonded panels require high-pressing temperatures, which suggests increased

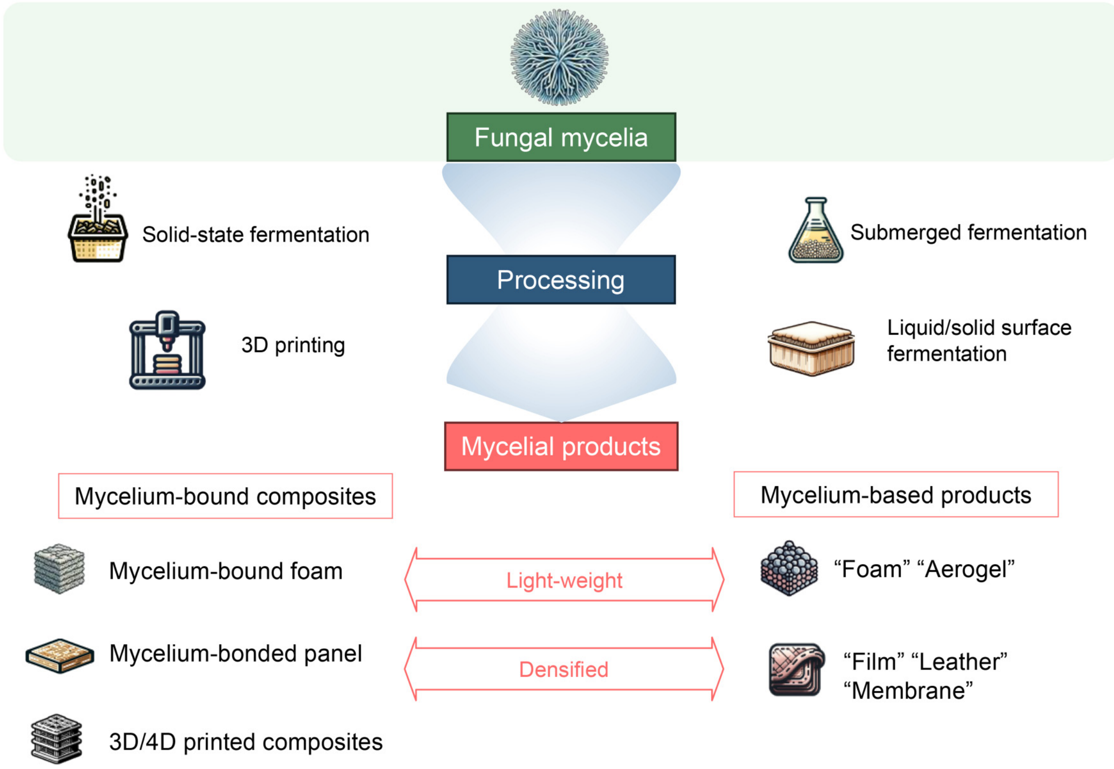

FIG. 1. Proposed classification and nomenclature of mycelial materials.

TABLE I. Characteristics and claimed advantages of representative mycelial products compared to their commercial counterparts, with associated and shared drawbacks and concerns.

Mycelial products	Competitive properties tested in the literature	Commercial counterparts	Other claimed features	Major drawbacks and concerns	Shared drawbacks
Mycelium-bound foam	Compressive strength Thermal insulation Acoustics insulation	Synthetic insulation foams	Fire resistance Surface hydrophobicity Reusability	High density Moisture sensitivity	Durability Limited scalability Limited in supply
Mycelium-bonded panel	Modulus of rupture Modulus of elasticity Internal bonding strength	Particleboard Fiberboard		High pressing temperature Moisture sensitivity	Expensive production facilities
Mycelium-based leather	Tensile strength Young's modulus Percent elongation	Animal leather Synthetic leather	Customizable properties Scrap-less confection process	Requires non-natural additives and modifications	
Living mycelial material	Self-healing Viability	None	Responsive to environmental stimuli	Requires specific conditions Safety Air quality	

energy consumption.[39] Common limitations, such as poor water resistance and a tendency to biodeterioration, could impact product longevity but are advantageous in terms of disposability.

The discussion around mycelial "leather" follows a similar narrative. Historically, leather has been prized for its enduring quality, designed for long-term usage. Derived from animal skin, a naturally resilient bio-based material, its durability is often enhanced through treatments incorporating non-eco-friendly additives.[40] In a similar manner, mycelium-based "leather" must undergo comparable processes to stand as a viable alternative to traditional leather. The significant demand and rapid production requirements for these items highlight the supply chain challenges, scalability issues, and production costs, factors that could potentially slow down their widespread market adoption.

Engineered living mycelial products, despite being an innovative concept with distinctive features such as self-repairing, are still in their infancy as a "next generation" material. While they present an exciting prospect, they may not yet offer a comprehensive solution to current environmental issues, particularly in the absence of commercial equivalents. Specialized cultivation requirements, along with potential health and environmental risks, warrant careful examination.

IV. DOES THE TYPE/CHARACTERISTICS OF THE MYCELIA MATTER?

As the primary and crucial component of mycelial products, it might initially appear unnecessary to question whether the type or characteristics of mycelia matters. Moreover, as many papers have addressed, one of the compelling aspects of mycelial materials is the vast diversity of fungal species that remain largely unexplored in the field of material science.[41] Even within the same species, significant variations exist among different strains.[42] All aspects of their characteristics, including but not limited to morphology, chemical composition, and growth rate, are highly tunable through environmental monitoring[43] and even genetic modification.[44] Numerous biological-oriented publications have affirmed these facts.[45]

However, it is notable that the current research on mycelial materials provides limited support for this extensive diversity. In the well-studied area of mycelium-bound composite foams, various studies have attempted to compare different species, seeking correlations between material properties and fungal characteristics, such as hyphae type,[46] fungal species,[47] and secreted enzymes.[48] However, these connections remain inconclusive. Most studies maintain consistent growth conditions and durations across different species, potentially overlooking condition-specific property outcomes. Studies examining the same species on different substrates[37] or under different growth times[32] both result in significant product properties and have further highlighted this fact.

It is also crucial to consider the role of mycelia in products, especially mycelium-bound composite. Studies have shown that in mycelium-bound foams, the dense and continuous mycelia network could strengthen the mechanical properties of the composite in a wet state, but they do not show a significant difference in the dry state.[46] Meanwhile, a study has also shown that mycelial colonization within the foam does not significantly alter physical and mechanical properties but can reduce sound absorption.[32] In contrast, increased mycelial density in hot-pressed panel products resulted in mechanical properties and acted as an adhesive to bond particles forced into contact during compaction.[32]

However, for pure mycelial products, as they serve as the primary building blocks of the entire material, the link between their inherent properties and the final product's characteristics is more direct. "Leather" films made from different fungal species, for instance, exhibit varying properties directly traceable to the fundamental attributes of the hyphae.[6] Yet, like with mycelium-bound composites, comparing different fungal types under the same processing conditions may not yield fair comparisons.

Despite the product type, application area, and usage stage, the question remains: How significant is the type and characteristics of fungal mycelia in mycelial products? While their impact is undeniable, other components can overshadow their importance. In mycelium-bound composites, the mycelia primarily act as a binder, rendering variations in type and characteristics less influential compared to changes in the main component, the substrate material. For pure mycelial products, additives, such as plasticizers, can significantly modify the material, categorizing it into different material families.[31] However, altering the fungal hyphae typically keeps the material within the same family. Thus, we must consider whether the type and characteristics of mycelia are as crucial as we initially thought.

V. RESEARCH METHODS, DIRECTIONS, AND CHALLENGES

As interest in mycelial materials intensifies, evidenced by a significant increase in academic research and the emergence of numerous startups in this field, this section explores the evolution of research and development efforts. The methodologies used, the future directions, the challenges encountered, and the gaps in current understanding and approaches in this rapidly growing area are summarized and discussed.

A. Evolution of mycelial material development

As highlighted in Sec. III, the applications of mycelial materials often parallel those of their non-fungal counterparts. This trend has been evident throughout new product development. For instance, foam-like and panel-like composites were among the first to be developed, with the initial patented and commercialized products introduced by Ecovative in 2007.[49] The development of pure mycelium-based products expanded subsequently. These have been commercialized as leather alternatives and, more recently, in various advanced applications have gained prominence in the literature over the past year, including masks,[50] Janus evaporators,[7] and wound healing devices.[8]

B. Processing technologies

Two distinct strategies have been established in the processing technologies for mycelial materials. The first involves adapting and evolving existing processes to suit mycelium-involved products, often inspired by the methodologies applied to their non-fungal counterparts or driven by new trends in advanced manufacturing.

For instance, the production of mycelium-bound composites follows traditional wood panel processes involving procedures like molding, oven-drying, or hot-pressing.[5] Additionally, advancements in manufacturing, such as 3D printing,[51] have also been explored to enhance structural design possibilities. In the case of pure mycelial materials, similar techniques, like wet-laid papermaking procedures, are employed.[52] The integration of fungal elements typically requires additional steps, including sterilization, inoculation, and incubation, usually preceding the aforementioned processes. Conventional processes, such as hot pressing and oven drying, effectively terminate the growth, thus eliminating the need for a separate termination process.

The second strategy adopts a more tailored approach, focusing on the unique features of fungi as living materials, which are yet to be utilized in traditional processing technologies. This involves innovative techniques such as employing semi-solid/liquid surface fermentation and controlling environmental conditions to cultivate pure mycelia on substrates[52] and indirect inoculation on preconstructed structures.[12] While this strategy offers new possibilities for innovation and application, it faces greater challenges in scaling up and commercialization compared to the first, which primarily involves modification to existing production lines. However, pioneering companies like Ecovative and Mycoworks have successfully commercialized such materials, demonstrating the feasibility of this approach.[52]

C. Improvement strategies

Due to the fundamental similarities with non-fungal counterparts, efforts to enhance mycelial materials often mirror those used for traditional non-fungal materials. These improvements typically involve material modifications, hybridization with other materials, and post-treatments such as coating and lamination. For example, hybridization in both composites and pure materials, comparable to methods used in conventional composites, includes incorporating reinforcing agents such as nanocellulose[53] or clay[54] into mycelium-bound composites, adding plasticizers and cross-linkers in mycelial films,[6, 31] and integrating gelling agents into 3D printing mycelium-bound structures.[10] Modification of the mycelium is more suitable for use for pure materials. In composites, the growth of mycelia themselves inherently alters the physical and chemical properties of the substrate. Applying chemical modification to the mycelial hyphae, such as acidic or alkaline treatments, can dramatically change the properties of the pure mycelial materials.[55] This leads to a recurring question from Sec. II: when essential components are lost, can those still be considered mycelial materials?

Adding a functional or protective layer by coating or lamination to both composite and pure mycelial products is a common and practical method. This approach can borrow various methods from wood composites or the textile industry, as well as numerous lab-scale methods detailed in scientific publications and patents. For instance, coating mycelium-bound composite with Osmo oil-based coating can enhance their resistance to tropical weathering conditions.[56] MOGU has developed floor tiles using mycelium-bound fiber waste as a core material, topped with a 90% bio-based resin coating, a bio-polyurethane (PU) layer, and a moisture barrier layer.[57] Similarly, binding a polylactic acid film onto the surface of mycelium-based films can increase strength and durability while maintaining product flexibility.[58]

Therefore, the anticipated trajectory of mycelial materials development can be foreseen by examining their counterparts in existing composites and natural fiber-based products. This parallel allows for the direct application of numerous strategies already documented in the literature to mycelial materials. However, we also need to be aware that integrating these strategies into mycelial materials is more complex than it appears due to the distinct nature of fungi as living materials. Ensuring fungal viability is a critical factor when modifying components or processes, as fungi require specific environmental conditions and nutrients for growth. For example, while additives like latex and silane coupling agents may enhance the mechanical properties of the composites, they could also impede fungal growth.[54] In the case of pure mycelial materials, introducing additives prior to growth can present similar challenges; even if they do not inhibit growth, they may alter crucial properties such as morphology and chemistry,[15, 59] which may not be the desired changes. Therefore, post-cultivation modifications, which are more favored in both commercial and laboratory settings, offer a more viable approach. Moreover, such post-treatment processes are often more compatible with existing conventional methods, as seen in the processing of mycelium-based leather substitutes.

D. Understand the fundamentals

Alongside technological advancements, a comprehensive understanding of the molecular and chemical fundamentals, along with knowledge of the alterations occurring at different processing stages, is key to controlling the final properties of mycelium-based products. This includes understanding how fungi interact with substrates, impact environmental and genetic changes, and how these affect the properties of the material, which includes cell wall composition, hyphal morphology, and growth behavior for pure mycelial products as well as those characteristics of substrates for mycelium-bound composites. The influence of those changes on processing techniques and final product properties also needs to be understood and evaluated. Although biologists have extensively documented fungal metabolism and adaptations, the connection between these biological aspects and material science, particularly regarding the final product's properties, is not well-established. This is partly due to the system's complexity, involving living cultures that undergo incubation and subsequent inactivation processes.

Research in this area has started to reveal insights into some of these aspects. For example, studies using simplified systems have examined the adhesion mechanism at the mycelium-substrate interface. Results show that the presence of a surface aerial mycelium layer significantly enhances bonding, with exopolysaccharides and proteins playing a crucial role at this interface.[60] This finding is particularly relevant in high-density, hot-pressed panel structures where mycelium also aids bonding by filling gaps.[32] However, the complex molecular details of these processes remain largely uncharted, and the applicability of these theories to different fungal and substrate systems has not been fully confirmed. Similarly, approaches like deleting the hydrophobin protein gene have been shown to improve mycelium density and mechanical strength,[44] but such findings have yet to be replicated across various fungal systems.

E. Environmental impact, safety, and economic viability

Expanding upon the essential aspects of mycelial materials, recent studies have started to focus on evaluating their environmental impact, safety, and economic viability. Life cycle assessments have shown that these materials typically have lower environmental impacts than their commercial counterparts, such as expanded polystyrene, conventional construction bricks, and conventional leather, except in specific categories. Key energy consumption arises from processes like sterilization, incubation, heat termination, and challenges associated with transportation and scaling up production.[61–65] Risk assessments also emphasize the necessity for standardized production processes to ensure safety and consistency, addressing risks like pathogenicity and mycotoxin production.[66] Furthermore, an economic assessment of mycelium-bound composite in construction suggests their cost-effectiveness under certain market conditions.[67] However, research in these areas is limited and challenging due to the limited availability of data, complex and evolving production processes, specific requirements for risk assessment, fluctuating economic variables, and more. This underscores the need for ongoing, detailed studies to fully understand and optimize the use of mycelial materials.

VI. CONCLUSION

Fungal mycelia, as naturally derived, renewable materials, hold increasing significance in the shift toward a circular economy. The development of standardized nomenclature and clear definitions is critical for the progression and clarity in this evolving field. The diversity and characteristics of mycelia, while critical, have shown varying impacts on product properties, necessitating further research. Mycelial materials, while innovative, need to demonstrate their effectiveness by equaling or surpassing the properties of traditional, non-sustainable materials. Comprehensive assessments encompassing physical, mechanical, environmental, risk, and economic factors are vital for the development and scientific analysis of these materials, ensuring their viability and sustainability in diverse applications. The future of mycelial materials in sustainable development is promising, requiring committed research efforts, broad collaborations across industries and academia, and supportive regulatory frameworks to fully realize their potential and ensure responsible adoption in our evolving material landscape.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Ethics Approval

Ethics approval is not required.

Author Contributions

Wenjing Sun: Conceptualization (lead); Writing – original draft (lead); Writing – review & editing (lead).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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