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MYCELIUM-BASED MATERIALS: AN ALTERNATIVE FOR SUSTAINABLE INTERIOR DESIGN

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Abstract. The constant growth of the construction industry is causing large-scale energy consumption and the depletion of natural resources. There is an urgent need for interior designers to change their interior construction and material usage strategies to promote reusable construction methods, use of recyclable materials, and reduction of energy consumption. Although efforts have been made to slow the negative effects of construction on the environment, they have not prevented the Earth's ecosystems breaking down. With this problem in mind, responsible interior designers are seeking new technologies that could help them develop sustainable alternatives to conventional interior design solutions. While several studies have discussed mycelium-based materials, few have considered the potential role of these materials in interior design. To address this gap, the objective of this paper is to explore mycelium-based materials and their interior design applications. A systematic literature review (SLR) was carried out to explore the sustainable characteristics and applications of mycelium-based materials. A qualitative research methodology based on a meta-synthesis approach was employed to comprehensively analyze and interpret relevant data across the selected publications. This paper aims to explore the sustainable characteristics of mycelium-based materials by studying fabrication methods and properties while determining possible applications in interior design. In conclusion, mycelium-based materials prove their potential as a sustainable alternative for replacing conventional materials through various experimental prototypes. Future development of these novel material characteristics will raise production to a scale capable of significantly contributing to the preservation of natural resources and development of a sustainable circular economy.

Keywords: *interior design, mycelium-based materials, sustainable interior design, sustainability, bio-based materials, sustainable materials.*

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1. Introduction

The world's human population, along with its habitation needs, have rapidly increased, leading to natural resource depletion and threatening the future of ecological systems. Traditional interior design and construction industries impose stress on the environment, since conventional materials are manufactured through the extraction of natural resources and demand high energy consumption (Van Wylick *et al.*, 2022). Moreover, the production of interior materials increases waste generation, while associated transportation and demolition processes pollute the air, soil, and water bodies and emit a significant amount of global greenhouse gas (Alemu *et al*., 2022). Hence, an emerging challenge for interior designers is the transformation from a highly

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consumption-oriented perspective to one that is more ecologically and environmentally responsible (Tucker, 2014). Interior designers are morally responsible for playing their part in protecting, preserving, and restoring the global ecosystem (Rashdan, 2015). Sustainable interior design can be defined as the rationalization of natural resources to address design impacts on the environment (Rashdan & Ashour, 2017). Interior designers are scrambling to envision alternative methods for tackling urgent sustainability issues (Ashby, 2013). To achieve these aims, they must be equipped with updated technologies that increase sustainability (Kang & Guerin, 2009). Designers, for example, are considering shifting toward more renewable building materials, such as engineered timber and bamboo composite and natural sheep wool, hemp, and flax boards (Florea & Manea, 2019), although these materials consume additional natural resources such as soil and water (Bitting *et al*., 2022). Another solution that has emerged in the last decade is biotechnology. The acceleration of advancements in biotechnological skills and knowledge transfer has led to the development of advanced bio-based materials as a possible innovative alternative to conventional materials (Attias *et al*., 2019; Álvarez-Chávez *et al*., 2012).

Bio-based materials developed by bacteria, algae, or fungi are distinguished by their low impact on the environment, renewability, and high rate of biodegradability (Bruscato *et al.*, 2019). Therefore, designers investigating bio-based materials have started to develop a different way of thinking about how to grow their materials and even how they can grow full designs, such as pieces of furniture. Consequently, bio-based materials really have the potential to replace fossil-based and synthetic materials (Van Wylick et al., 2022). Mycelium-based materials are an example of bio-based materials that show promise as sustainable candidates for replacing traditional materials, especially since they can be produced from varieties of waste agriculture feedstocks (Kim & Ruedy, 2019). These materials have been investigated over the past decade, and their circular life-cycle model has proved to be viable in interior design. They are self-growing, made of natural material, and, because they utilize the natural digestion mechanism of fungi, they can be used to treat regional organic waste. Moreover, these materials are lightweight, compostable, and regenerative. These morphological, physical, and mechanical properties of bio-based materials can be adapted by changing growth sources and conditions to enable genuine design applications in interior design construction (Modanloo *et al*., 2021; Antinori *et al.*, 2020).

Bio-based materials, which are produced from living organisms available in nature, can be produced in "cradle-to-cradle" production cycles. Materials based on agricultural waste (Dougoud, 2018) have been shown in several interior and design experiments to have the potential to be produced in a "cradle-to-cradle" manner.

Moreover, mycelium-based materials limit the consumption and waste of natural resources, are easily reused and recycled, and, at the end of their lives, biodegrade readily. The use of these materials provide a successful paradigm for the circular economy model in manufacturing interior design materials. (Purchase *et al*., 2021)

Considering the promise of mycelium-based materials, research has been increasingly focusing on the potential for it to replace conventional materials in interior design and reduce the negative impact of the interior design industry on the environment. By considering current available literature and existing experiments regarding the use of mycelium-based materials in the interior design industry, this paper aims to explore the potential of such materials to make the interior design industry more sustainable.

The objectives of this paper are i) identify mycelium-based material types and properties based on fabrication methods; ii) determine the possible applications of these materials in interior design while giving examples of said applications; and iii) discuss the sustainable characteristics of mycelium-based materials and their impact on the environment.

2. Research methodology

A systematic literature review (SLR) was carried out to explore the research question of whether the sustainable characteristics and applications of mycelium-based materials make them an alternative to conventional interior design materials. The SLR was carried out using specific research purposes, questions, and strict inclusion criteria. Thus, irrelevant documents were removed. Scientific research databases (Scopus, ScienceDirect, Google Scholar, ProQuest, and EBSCO) were used to generate relevant articles and books. Extensive research was carried out to determine related design exhibitions and online resources.

A three-step process was followed to retrieve the articles (Figure 1): i) identification based on keywords extracted from the research question (Table 1); ii) screening and eligibility by reviewing research results based on title and abstract while excluding duplications and publications that were not in English or not peer-reviewed; and iii) inclusion based on evaluation criteria that measured the relevancy of the content of the full documents. The inclusion criteria were assessed based on a 5-point scale, and only the publications and online resources that scored at least 3 out of 5 were considered (Table 2). The search was completed on 15 September 2022, and a total of 51 publications were retrieved from the searched databases and 10 online resources.

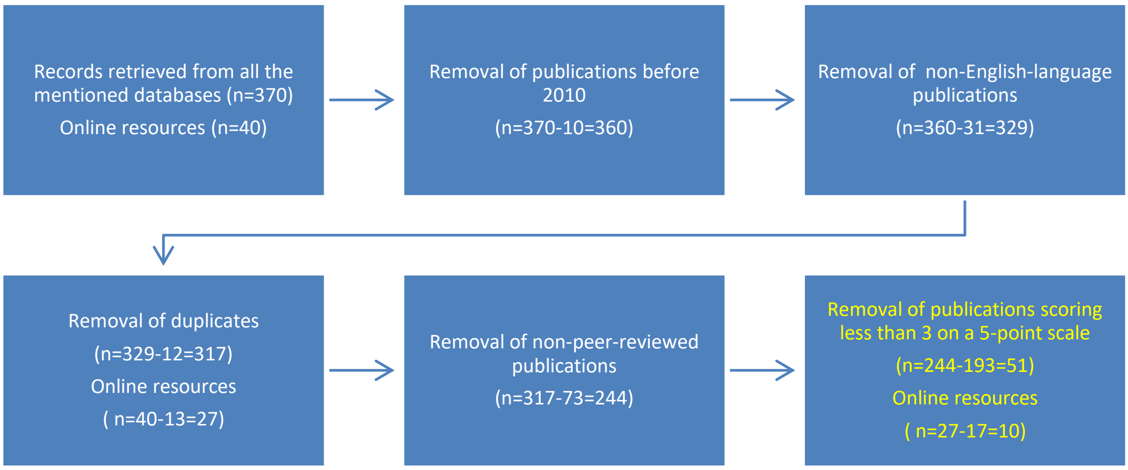

Figure. 1. Flowchart of the literature review process (Authors, 2022)

Table 1. Search keywords

Database search keywords
mycelium-based materials; mycelium-based composites; pure mycelium, fine mycelium, mycelium-based materials sustainability, mycelium-based materials properties; mycelium-based characteristics; mycelium-based materials applications; interiors mycelium-based material; construction mycelium-based materials; experimental applications in mycelium-based materials; mycelium-based furniture, mycelium-based insulation materials (Authors, 2022).

Table 2. Inclusion assessment criteria (Authors, 2022)

Criteria	Description	Score
Publication inclusion assessment criteria (C#)		
C1	Discussing the sustainable characteristics of mycelium-based materials	2
C2	Discussing the applications of mycelium-based materials' in interior design and relevant fields	1.5
C3	Comparing the properties of mycelium-based materials' with those of conventional design materials	1
C4	Considering the different types and manufacturing processes of mycelium-based materials	0.5
	Total Score	**5**
Online resources inclusion assessment criteria (CO#)		
CO1	Pioneer companies and/or designers with a proven record in the field of mycelium-based materials	1
CO2	Mycelium-based materials employed in experimental and/or existing projects	2
CO3	Registered a patent supporting manufacturing of mycelium-based materials	2
	Total Score	**5**

In summary, the topic of mycelium-based materials is relatively new; therefore, most of the journal papers on the topic have only been published recently. An examination of 244 publications revealed that only 51 scored 3 and above on the inclusion assessment scale, namely five books, one doctoral dissertation, one master's thesis, four conference proceedings, and 40 journal papers. In addition, 10 online resources relating to pioneer companies and designers in the field of mycelium-based materials were identified.

A qualitative research methodology based on a meta-synthesis approach (Mengist *et al*., 2020) was considered to be suitable for comprehensively analyzing and interpreting relevant data across the selected publications. The authors identified each study's key metaphors, phrases, ideas, concepts, relations, and, in particular, tabulated findings related to the mycelium-based materials within the interior design context. The meta-synthesis process began with selecting, appraising, coding, and summarizing before the qualitative evidence was combined, integrated, and synthesized to address the research objective. Reliability was achieved by replicating this process with all selected references, thus validating the results obtained.

3. Mycelium-Based Materials

Mycelium-based materials result from the growth of filamentous fungi on organic materials, such as agricultural waste streams and by-products, which are available across the globe in large quantities and at low cost (Jones *et al*., 2020; Appels *et al*., 2019). The first explorations of mycelium to as a building material were initiated by Shigeru Yamanaka (Girometta *et al*., 2019). Recently, designers have started to explore a wide range of potential uses of mycelium-based materials, and have created new applications and provided sustainable alternatives to conventional materials in areas such as interior design, furniture, fashion, and architecture (Ghazvinian, 2021). Such applications promise to bring revolutionary changes in the paradigms of internal design sustainability.

Mycelium is the fibrous root system of fungi that absorbs nutrients from the soil (Ghazvinian *et al*., 2019). Fungi mycelium functions as a decomposer of organic matter and gradually colonizes organic matter while interweaving it within a three-dimensional fiber network (Manan *et al*., 2021). Because of the ability of fungi to grow quickly and to decompose organic material effectively, bio-based materials can be produced from local agricultural waste (Attias *et al*., 2020).

Fungal mycelium is a complex network of interlaced microscopic fibers (hyphae) (Attias *et al*., 2020). Hyphae are long, branching filamentous structures of fungi that act as growth agents (Ghazvinian *et al*., 2019). Mycelium hyphae secretes enzymes that break down biopolymers to more superficial bodies and then digests organic fiber nutrients (substrate) (Angelova *et al*., 2021). This process lets the mycelium colonize the organic substrates and increase their biomass while creating either a fluffy or a compact layer called fungal skin, which covers the substrates (Manan *et al*., 2021; De Ulzurrun *et al*., 2017). In this way. mycelium-based materials result from the growth of mycelium on organic substrates, such as wheat, hemp, kenaf, and flax residues, under controlled environmental conditions (Attias *et al*., 2020).

4. Mycelium-based Materials Production

Mycelium-based materials are obtained after it is dehydrated, and they result from the complete degradation of substrates during colonization. The two primary methods of production result in two different types of such materials: 1) mycelium-based composites (MBC) and 2) pure mycelium materials (PMM) (Bitting *et al*., 2022). However, the production of both types of mycelium-based materials follows a similar procedure. To ensure production sustainability, the researchers focused on the use of production systems that rely on renewable energy. However, the procedures for producing mycelium-based materials described in the following paragraph are commonly used.

Initially, the mycelium is grown on agar plates, in a grain substrate, in a liquid nutrient solution, or on a homogenized substrate (Elsacker *et al*., 2020). In the case of MBC, the organic substrates may be humidified before the sterilization process, which is recommended, or sterile water may be added after sterilization (Modanloo *et al*., 2021). The substrate is sterilized by solar autoclaving or treated with chemical or microbial agents to eliminate any type of microorganism, thereby preventing contamination during the growth process (Elsacker *et al*., 2020). After the sterilization step, all equipment, tools, and materials involved in the process are sterilized (Nashiruddin *et al*., 2021). The substrate is inoculated through the addition of an appropriate amount of the selected mycelium tissue. A mold of the final design form is then prepared and filled with the inoculated substrate. To ensure stable growth, the mold is left under controlled environmental conditions of light, temperature, and moisture (Butu *et al*., 2020). The growing process takes a few days to weeks, depending on the size and required properties. The material can be grown in two phases: first, in a mold where mycelium colonizes the fibers and second, outside the mold to solidify the outer skin of the material (Elsacker *et al*., 2020). The mycelium-based materials thus grown are dehydrated in a solar oven to end the growth process.

Many variables influence the growth of mycelium-based materials. These include the characteristics of the substrate type used, the inoculated fungi strain type, additives used, growing environmental conditions (i.e., humidity, temperature, and supplementation), dehydration process, pressing process (i.e., hot, cold, or non-pressed), and forming techniques applied (Jones *et al*., 2020; Ghazvinian *et al*., 2019; Appels *et al*., 2019; Girometta *et al*., 2019; Heisel *et al*., 2017). Altering the growth process variables can enhance the properties and physio-mechanical performance of mycelium-based materials to make them more suited to certain needs, such as specific structural and functional requirements, including thermal and acoustic insulation, bearing load, and fire resistance (Jones *et al*., 2020; Attias *et al.*, 2019; Haneef *et al*., 2017).

5. Mycelium-based Composites (MBC)

MBC materials are produced by utilizing digital fabrication or by growing mycelium on solid organic substrates guided by a specific mold or scaffold (Elsacker *et al*., 2020; Jones *et al*., 2017)., The procedures related to substrate preparation and inoculation of mycelium-based materials to grow a composite within a mold are as follows. Two steps are recommended to achieve the best results during the growth process: The first step is to grow the inoculated substrates in chambers under controlled environmental conditions until enough mycelium cultivation samples are produced; The second step is to transfer the cultivation samples to be incubated into a mold to form the desired shape (Ghazvinian *et al*., 2019). Plastic sealed molds are commonly used in industrial manufacturing to maintain a constantly controlled environment for fungal propagation (Bitting *et al*., 2022). However, during incubation, the fungal mycelium gradually colonizes the substrate fibers and enforces fiber while bonding the substrate material (Attias *et al.,* 2019). Once the growing process is complete, the assembled MBC is dried in order to halt and terminate the growth process, with the end result being a highly renewable and biodegradable composite.

Some designers are experimenting with different MBC production methods. Nguyen et al. (2022), for example, utilized the skeleton reinforcement structure method, which grows mycelium on a fibrous scaffold using fibrous mats. Another technique employs digital fabrication, utilizing 3D printers to print cellulose scaffolds. Experimental methods have faced some difficulties in maintaining the final form layout, but merging these methods and using molds in fabrication enhances final product properties, such as bearing load and durability, making MBC more suitable for interior and furniture design.

Mycelium-based bio-composites are highly porous and lightweight materials. They have a relatively low density compared to plastics, although they are denser than expanded polystyrene (EPS) (Nashiruddin *et al.,* 2021; Schritt *et al*., 2021). MBC contain high-performance natural insulators derived from agricultural waste. They are natural fibers bound using mycelial growth and have thermal conductivities of (0.04–0.08 W/m·K) (Butu *et al*. 2020), making them excellent insulation materials compared to conventional commercial thermal insulation products, such as glass wool (0.04 W/m·K) and extruded polystyrene (XPS) insulation (0.03 W/m·K) (Jones *et al*., 2020; Asdrubali *et al*., 2015).

Due to their fibrous and porous nature, MBC act as a frictional element, resist acoustic wave motion, and absorb more than 70% of sound (Pelletier *et al*., 2013). Thus, they may be able to reduce sound wave amplitude and play an important role in acoustic absorbance (Manan *et al*., 2021). Hence, the acoustic insulation of mycelium-based composites is likely to be competitive with that of fossil-based materials: Polystyrene foams, for example, have been shown to achieve 20–60% absorption, while polyurethane foams have been shown to attain 20–80% absorption (Jones *et al*., 2020). Moreover, all MBC that have been tested have been associated with lower perceptual road noise. The best individual substrate fillers for acoustic absorption were rice straw (52 dba), hemp pith (53 dba), flax shive (53.5 dba), sorghum fiber (54 dba), and switchgrass (55 dba).

The compression of material and the spaces between fibrous structures causes a reduction in acoustic absorption (Jones *et al*., 2020).

Another advantage of MBC is that they possess better fire retardancy features than conventional synthetic insulation materials used in construction, such as polystyrene and polyurethane foams, which are very flammable (Ghazvinian, 2021; Sydor *et al*., 2021). According to Jones et al. (2020), MBC containing 75% rice hulls have lower average and peak heat release rates (107 kW/m^2 and 185 kW/m^2, respectively) than synthetic foams such as XPS insulation foam (114 kW/m^2 and 503 kW/m^2, respectively) and engineered woods, such as particleboard (134 kW/m^2 and 200 kW/m^2, respectively). Embedding silica in mycelium composite substrate increases its fire-resistant ability significantly. MBC are distinguished by lower production of Co, CO_2, and smoke on burning than conventional materials (Manan *et al.*, 2021; Jones *et al*., 2020).

MBC have a relatively low compressive strength compared to bearing-load conventional materials; compared to EPS, MBC have been shown to obtain up to three times higher compressive strengths (Schritt *et al.*, 2021; Bruscato *et al.*, 2019), while they are slightly weaker than polyurethane and phenolic formaldehyde resin (Nashiruddin *et al.*, 2021). Composites have the disadvantage of a lack of tensile strength, but heat pressing can enhance their flexural and tensile strength (Appels *et al.*, 2019; Islam *et al*., 2017). Moreover, it is possible that composites with adequate reinforcement can substitute for traditional masonry units (Ghazvinian *et al*., 2019).

6. Mycelium-based Composite Applications

Several experiments have been conducted over the last decade to explore the potential of MBC as alternatives for a wide range of design application materials (Attias *et al.*, 2019; Ghazvinian *et al*., 2019). The flexural strengths and stiffness of MBC, their thermal and acoustic insulation, and their fire resistance are better than those of most commercial thermoplastics. These properties mean that MBC resemble natural materials, such as wood and cork, and that they can be used to replace non-sustainable fossil-based and synthetic materials, such as polyurethane and polystyrene, in interior design insulation applications, such as acoustic floors and ceiling tiles and fillers for thermal and fire resistance doors and panels (Jones *et al*., 2020; Bruscato *et al.*, 2019; Elsacker *et al.*, 2019). Mogu, Biohm, and GROWN bio are pioneer companies that have introduced mycelium wall and ceiling panels, either bare or covered with resin-like coatings, for use as insulators (Figure 2).

a b c d

Figure 2. Examples of MBC applications in interior design
a. Acoustic tiles by Mogu (Mogu Admin, 2022); b. Floor tiles by Biohm (Biohm, 2016); c. Wall tiles by GROWN bio (GROWN bio Admin, 2022); d. panel insulation by GROWN bio

Lightweight and biodegradable MBC have encouraged designers such as Phil Ross, Erik Klarenbeek, and Jonas Edvard to explore ways for designing mycelium-based furniture (Ghazvinian, 2021). Companies such as Krown7, Ecovative Terreform One8, Blast Studio9, Officina Corpuscoli, and GenSpace10 have started to produce light fittings and furniture using mycelium-based biocomposites. Product designers also use mycelium as part of their furniture designs. Figure 3 shows items of furniture that have made significant strides toward replacing conventional materials with MBC.

a b c

Figure 3. Examples of MBC applications in furniture
a. Chair and light unit by the Growing Lab design (Montalti, 2022); b. Stack table (GROWN bio Admin, 2022); c. Chair by Philip Ross (MycoWorks Admin, 2022)

Another application for MBC is as a building material for small structures, such as masonry units. The Hy-Fi Tower is a successful experiment that shows the potential of MBC in building construction, proving their durability, resistance, workability, and sustainable life cycle. This temporary structure was designed by David Benjamin from Living Studio and ARUP13 in 2014 for MoMA's PS1 courtyard. Three months later, it was disassembled, broken up, and mixed with soil to be composted. Approximately 10,000 mycelium bricks were used to build the three 13-meter-high cylinders that made up the tower (Ghazvinian *et al*., 2019; Rebecca & ARUP, 2014).

Another experiment is the Shell Mycelium pavilion by Yassin Areddia and Beetles 3.3, which was designed for the 2017 Seoul Biennale of Architecture and Urbanism as an example of employing mycelium as a reliable substitute for concrete in small-scale and temporary construction projects (Heisel *et al*., 2017).

Phil Ross designed the Mycotecture Alpha teahouse in 2009 as an example of possible usage of mycelium-based bio-composites. It is a simple, relatively small barrel vault design and a structure consisting of approximately 350 mycelium blocks with a mycelium floor (Karana *et al*., 2018; Andrea, 2012).

Lastly, the Growing Pavilion, designed by a team led by Pascal Leboucq as an event space, was constructed with biomaterials, with the external façade being made of panels grown from mycelium. The panels are attached to the timber frame of the pavilion and can be removed and repurposed after utilization (The Growing Pavilion, 2022). Figure 4 shows examples of MBC applications in architecture.

a **b** **c**

Figure 4. Examples of MBC applications in architecture
a. Hy-Fi Tower (Rebecca & ARUP, 2014); b. Mycotecture Alpha teahouse by Phil Ross (Andrea, 2012); c. the Growing Pavilion (The Growing Pavilion, 2022)

7. Pure Mycelium Materials (PMM)

Another fungal material is pure mycelium, which is the result of the complete degradation of the substrate and is fabricated from a liquid culture in which the mycelium is provided with the nutrients necessary for its growth (Vandelook *et al*., 2021). The liquid fermentation of fungal microorganisms can occur in static or machine-shaken containers. When grown in a static liquid culture, filamentous fungi form a mat of hyphae on the surface of the liquid (Butu *et al*., 2020).

The basic method for producing these mycelial biopolymers starts with several containers, each of which defines the cavity that contains a soft scrim, the nutritive substrate, and the desired fungal strain. These containers are subsequently placed in a closed incubation chamber with airflow directed at the target humidity level and temperature (Bitting *et al*., 2022; Haneef *et al*., 2017). The use of bioreactors meets the need for a controlled environment with the potential to produce large quantities of material (Shokrkar *et al*., 2018).

The resulting substance is a mycelium fibrous film that forms thin sheets of material and is obtainable by “removing the fungal skin from the substrate” (Appels *et al*., 2019; Ghazvinian, 2021). After the drying process, the resultant materials can vary in their properties and resemble paper, plastic, or leather, distinguished by flexibility, durability, and waterproofing (Bitting *et al*., 2022; Ghazvinian, 2021). Different colors, degrees of stiffness, and translucency effects can be obtained depending on the additives, such as glycerol or ethanol, provided to the mycelium at the end of its cultivation (Butu *et al*., 2020; Appels *et al.*, 2019; Karana *et al.*, 2018; Blauwhoff, 2016). The strength of pure mycelium-based materials can be increased by 300% by mixing sand with wood chips, since the water-holding capacity of materials will be increased by adding silica, methylcellulose, and agarose (Manan *et al*., 2021; Jones *et al.*, 2017).

Pure mycelium has several applications in fashion accessories, such as belts, shoes, and wallets. In the context of interior design, pure mycelium is utilized to produce synthetic leather to replace animal leather in furniture upholstery, as in the work produced by MycoWorks (MycoWorks Admin, 2022). Figure 5 shows examples of PMM and its applications.

a b

Figure 5. Examples of PMM and their applications
a. Pure mycelium materials (Officina Corpuscoli, 2022); b. Leather-like mycelium (MycoWorks Admin, 2022)

8. Mycelium-based Materials' Sustainable Characteristics

Interior designers can effectively contribute to efforts toward sustainability through their role in determining manufacturing and consumption models (Kang & Guerin, 2009). They can apply sustainable strategies, such as recycling, reducing, and reusing; controlling energy and water consumption; using efficient materials and furnishings; and developing healthy indoor environments with low carbon footprints (Rashdan & Ashour, 2017). The alarming rate of human population growth, accompanied by technological improvement, has encouraged responsible interior designers to look for alternative design models that transcend the conventional problem-solving approach and explore new production paradigms for their design materials to save the environment from resource depletion and pollution (Alemu *et al*., 2022). This approach encourages biodegradable materials research, which aims to produce new materials that are not harmful to the cycles of the ecosystem and thus reduce the impacts of synthetic polymer material residues on the environment (Väisänen *et al*., 2017).

One of the resultant paradigms is bio-based materials, which are biodegradable, sustainable, natural materials manufactured from organic waste and which can be turned into structural and stable materials. Such materials provide a sustainable alternative and offer more holistic and resilient sustainable interiors and promise a utopian life of consumption in which there is limited waste and design elements are composted (Clark, 2013). Recent studies have pointed out that it is possible to replace conventional materials with bio-materials produced from the mycelium substrate complex (Maximino *et al*., 2020). Mycelium-derived materials have several key advantages over conventional synthetic materials, including their low cost, low density, eco-friendly nature, and energy consumption (Alemu *et al*., 2022; Escaleira *et al*., 2021). Mycelium-based materials have a positive life cycle assessment (LCA; this assessment aims to measure a product's impact from the extraction of raw materials to the end of life) rating and thus can be regarded as an example of the sustainability concept of "cradle-to-cradle" (Figure 6).

Six principal factors underlie the sustainability of mycelium-based materials and their potential to play a significant role in the future of sustainable interior construction.

First, bio-based materials generally grow from almost inexhaustible organisms, such as fungi, bacteria, and algae, which are easily reproducible and abundantly formed in terrestrial and marine ecosystems (Camere & Karana, 2017). Mycelium-based materials are produced by growing mycelial networks on abundant agricultural waste and natural fiber substrates (Elsacker *et al*., 2020; Jones *et al*., 2020). Mycelium-based materials enable agricultural waste and lignocellulosic biomass to be exploited. They make use of waste and residues rather than discard them, leading to lower prices as cheaper raw materials are used (Maroušek *et al*., 2015). Moreover, since all production components can be grown, this approach has no limitations regarding resources (Nguyen *et al*., 2022). Finally, mycelium-based products are produced based on highly renewable fungus organisms and the environment benefits from the recycling of organic waste.

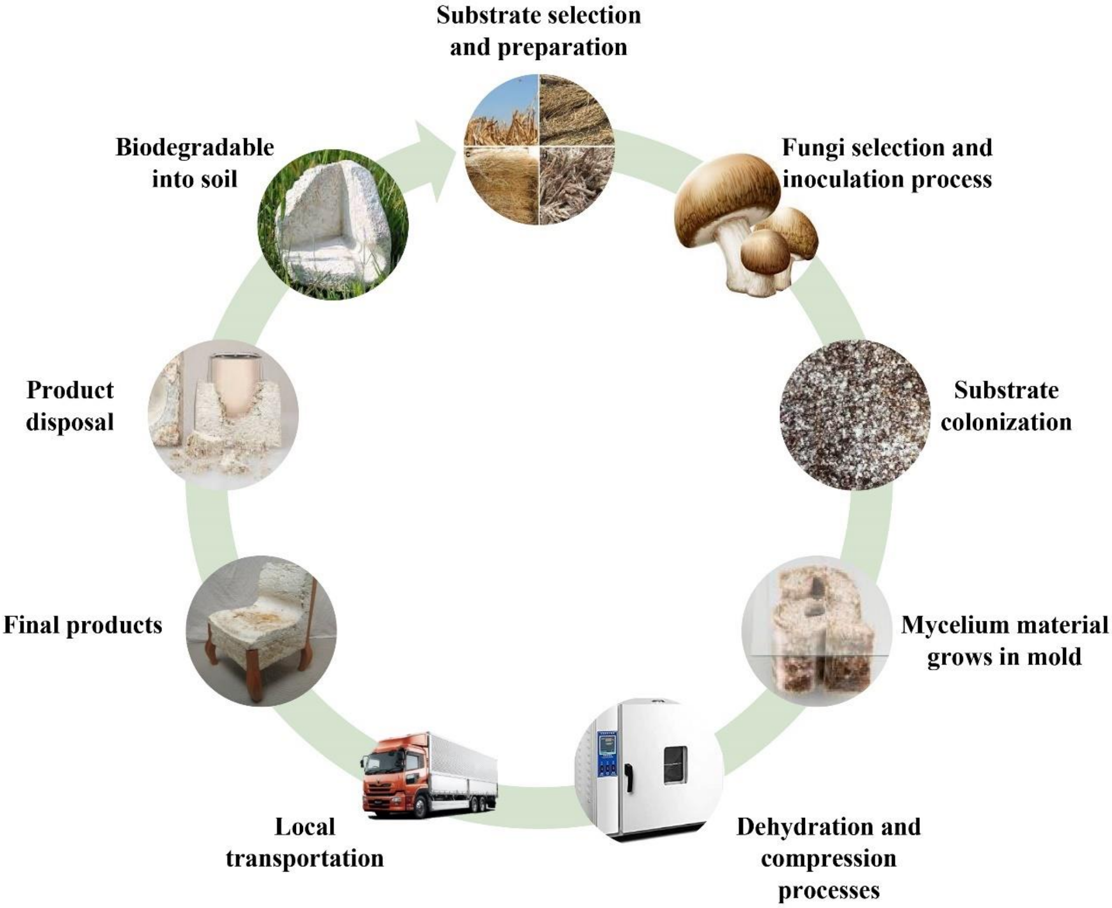

Figure 4. Mycelium-based materials' sustainable life cycle (Authors, 2022)

Second, artefacts made from conventional natural materials from raw matter may take years or centuries to form. In contrast, the production of mycelium-based materials is fast—taking just a few days or weeks—and thus these materials can be quickly and efficiently produced.

Third, a significant environmental advantage of mycelium-based materials is that they are self-growing rather than manufactured. Hence, the production process of these materials does not use any fuels, hazardous reagents, or rare catalysts (Nashiruddin *et al.*, 2021). In contrast to many plastics and synthetic materials, a moderately embodied energy is required to produce mycelium-based materials since their growth conditions can be controlled with low energy use and their biological activity may be halted during the drying process. However, solar energy can alternatively be used to achieve a very low-carbon to carbon-free footprint (Antinori *et al.*, 2020). Moreover, in the mycelium-based materials prototype, regional agricultural waste products can be used as the raw materials (Alemu *et al*., 2022; Nashiruddin *et al*., 2021), thus reducing the need for transportation of resources and products. This is another way in which mycelium-based material production decrease environmental pollution.

Fourth, most natural-based solutions require synthetic binders to enhance their properties and so such materials are nondegradable. Mycelium, however, acts as a natural glue that binds substrates together to form materials that are non-toxic and free from harmful chemicals (Van Wylick *et al*., 2022; Krivanek, 2020).

Fifth, bio-based materials are made solely of natural substances, meaning that they can be discarded in nature and used for a wider range of applications (Crabbé *et al*., 2013). After use, mycelium-based materials are biologically fully compostable, biodegradable, and can be recycled without harming the environment (Escaleira *et al*., 2021; Peters, 2014). In certain cases, glue, varnish, or coating is added to mycelium-based materials to significantly improve their physical and mechanical properties, practices which, unfortunately, negatively affect their biodegradability (Girometta *et al.*, 2019). However, if no synthetic additions are made to the final products, mycelium-based materials can be recycled into feedstock for packaging or composite core material, so diverting waste from landfill, or broken down and made into an excellent fertilizer (Jiang *et al*., 2016). Mycelium materials can be shredded and buried in damp soil. It should be noted that, considering the moist conditions that favor microbial degradation, the natural biodegradation of MBC will depend on bacterial degradation and the activity of insects (dipteran, coleopteran) and mites, (Nashiruddin *et al*., 2021; Girometta *et al*., 2019). That said, these novel materials represent a promising and environmentally friendly alternative to commonly used conventional materials in terms of sustainable manufacturing processes and circular lifespans (Appels *et al*., 2019).

Sixth, mycelium-based materials are distinguished by their flexibility in terms of mechanical and physical properties, which makes them suitable replacements for several conventional insulation and structural materials in interior design. The great number of possible combinations that result from using several fungal strains and a wide range of substrates mean that mycelium-based materials have a wide range of properties (Antinori *et al*., 2020). The materials' properties can also be adapted by changing the growth process factors (Angelova *et al.*, 2021). Therefore, mycelium-based materials can offer numerous futuristic sustainable materials to be used in many applications that need materials with different properties.

9. Discussion

Considering rapid industrialization, the constant growth in material consumption, and the critical waste problems in interior design, it is clear that sustainable and feasible solutions for natural, recyclable, and biodegradable alternative materials need to be found. We can consider materials environmentally friendly when they produce less pollution and waste during manufacturing, utilization, transportation, and demolition processes, and, at the same time, are economically feasible. Following this definition of sustainable materials, we have observed that most conventional interior construction materials, such as cement, gypsum, and polymers, are characterized by durability, high compressive strength, and resistance to weathering conditions. They are manufactured from finite natural resources, causing pollution from production through demolition; moreover, they are mostly nonrecyclable, consume energy, emit greenhouse gas, and incur high costs. At the same time, excessive usage of natural wood products in interior design and construction leads to deforestation and unexpected weather fluctuation as a consequence.

The increasing shift toward more renewable building materials, such as mass engineered timber and engineered bamboo composite, consumes additional natural resources, such as soil and water, and there is wide usage of synthetic adhesives and finishing chemicals coats. This means that renewable materials can have a negative long-term environmental impact, such as by intensifying the volume and rate of deforestation worldwide. It is not necessarily guaranteed that materials based on renewable materials have a fully circular lifecycle.

Alternatively, the production of bio-resins and bio-plastics as alternatives to their more traditional petroleum-based counterparts typically relies on a single commodity feedstock. This causes a rise in demand for these feedstocks for industrial use, creating competition with existing stock for food supply and instigating complex socio-economic policy problems. Using biomaterials can reduce costs to about 80 times less than those of conventional materials and reduce carbon emissions by nearly 800 million tons per year. However, bio-based composites with mineral and petrochemical matrices are widely used, and their biodegradability is costly due to the complex separation of the composites into their initial components, which causes limited end-of-life options. The recyclability of composites with bio-based matrices is also limited, as degradation can occur only in specific industrial composting conditions.

Therefore, there is an urgent need to find new alternative materials that are not just naturally cultivated and harvested, but that are also produced with processes that repurpose waste and improve the life cycles of the materials produced. Mycelium-based materials can be considered eco-friendly materials that combine many mitigation strategies, such as recyclability and biodegradability, since the main constituents of MBC are fibrous substrates, lignocellulosic agricultural or forestry by-products, waste such as straw and hemp, or porous substrates such as sawdust. They also have low embodied energy and carbon emissions, are cost-effective due to self-growing properties, and entail a relatively easy manufacturing process. They minimize transportation costs and fuel by using locally available agricultural waste. Hence, mycelium-based matrices are organic and fully biodegradable, and thus meet the requirements of the circular material life cycle.

Mycelium-derived materials are environmentally friendly and have a very positive LCA. They start out waste-derived (fully renewable and recycled local sources) materials and the manufacturing process used to produce them entails a low energy consumption, has a low carbon footprint, and requires no synthetic additions, and, finally, they are fully biodegradable at the end of their life cycle.

The typical linear economic paradigm of “produce, use, and discard” means that the construction materials industry contributes significantly to global greenhouse gas emissions, the destruction of natural habitats, and the production of industrial waste. The construction industry has been shifting toward a more circular model in an increasing effort to address the environmental challenges caused by a linear economy. The circular economy refers to an economic model whose objective is to produce goods and services sustainably by limiting the consumption and waste of natural resources. A circular economy requires loops to be closed and should consider starting by reusing waste resources and ensuring that materials are recyclable and biodegradable when they reach the end of their life cycles. Mycelium-based materials satisfy the requirements of the circular economy model. They are fabricated from renewable ingredients, such as organic agricultural and industrial waste, and do not rely on mass extraction or exploitation of valuable finite or nonfinite resources. Mycelium-based materials have shown their potential as a more circular and economically competitive alternative to conventional synthetic materials in the fields of architecture, interior design, fashion, and furniture prototyping.

There have been three revolutionary changes in materials industrialization in the last few centuries. First, the invention of the steam engine in the 18th century led to development of machinery production. Second, in the early decades of the 19th century, electrical power enabled more dynamic production. While the third revolutionary change, namely the invention of computers and digital technologies in the mid-20th century, offered accuracy and reduction of material usage and waste. Rapid population growth accompanied by a discard culture that causes air pollution, global warming, and landfill waste has inspired designers to look for promising solutions to environmental problems. Hence, the authors argue that the emergence of novel bio-based materials has become the fourth industrial revolution, which is characterized by the concept of a return to nature, a focus on achieving a circular life span, and an aim to help environmental resources to recover. The latest revolution is based on changing the method of material thinking, which is essential for designers to convert their design ideas into physical artifacts. In the era of a return to nature, this is not limited to modifying traditional ways of dealing with materials, although doing so plays a critical role in reacting to and adapting bio-based materials as a design concept, where living organisms, such as bacteria, algae, or fungi, are essential components in the design and fabrication process. However, the authors can say that this shift requires modern thinking and technologies that could offer new sustainable paradigms as alternatives to the many synthetic materials customarily used in interior artifacts.

Hence, researchers in diverse disciplines have engaged extensively with the concept of employing biological mechanisms to produce sustainable products. Designers have collaborated with biologists and materials scientists to undertake tailored interdisciplinary scientific substantiation-based research to develop a circular bio-production paradigm while determining the characteristics of bio-based materials and enhancing their properties to make them more flexible, sustainable, and multifunctional, and able to self-assemble and self-heal. Natural bio-based materials are grown rather than manufactured and thus offer a range of fascinating potential ways to produce materials.

10. Conclusion

Bio-based materials will play a pivotal role in future sustainable solutions. Hence, research raising awareness of such materials is a crucial part of achieving sustainability.

The current paper highlights the use of mycelium-based materials as an alternative to conventional materials, especially fossil-based materials, that supports the transition to the circular economy model.

Mycelium-based materials have the potential for several applications in interior design as alternatives to i) synthetic planar materials, such as mycelium-based films and paper- and leather-like sheets; ii) larger low-density objects, such as insulation foams and door cores; and iii) semi-structural materials, such as paneling, floor and ceiling tiles, and furniture.

However, several factors limit their current application to small-scale prototypes: Production is undertaken by only a few companies in the world, standardization in production methods and material characterization is lacking, and a limited number of fungal species and types of agriculture waste are being explored for their contribution in the field of mycelium-based material.

Although mycelium-based materials have a low carbon footprint and are considered biodegradable, they are slowly replacing conventional materials, especially insulation applications in interior design.

Future research should focus on ways to increase adoption rates, try to uncover more possibilities for how emerging biological materials can be utilized in a sustainable production cycle (a cycle which requires much transdisciplinary collaboration and research aimed at enhancing the mechanical and chemical properties of biomaterials), and aim to determine requirements for large-scale production and ensure an integrative, mature, and holistic approach to the application of biomaterials. The time required to replace the current traditional materials could thus be reduced, and they could be made a practical and viable sustainable solution in interior design construction.

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