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Mycelium-based composites: An updated comprehensive overview

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ABSTRACT

Mycelium-based composites hold significant potential as sustainable alternatives to traditional materials, offering innovative solutions to the escalating challenges of global warming and climate change. This review examines their production techniques, advantages, and limitations, emphasizing their role in addressing pressing environmental and economic concerns. Current applications span various industries, including manufacturing and biomedical fields, where mycelium-based composites demonstrate the capacity to mitigate environmental impact and enhance economic sustainability. Key findings highlight their environmental benefits, economic viability, and versatile applications, showcasing their potential to revolutionize multiple sectors. However, challenges such as consumer acceptance, intrinsic variability, and the need for standardized guidelines persist, underscoring the importance of further research and innovation. By optimizing material properties and refining production processes, mycelium-based composites could pave the way for widespread adoption as sustainable materials, contributing to a greener and more environmentally conscious future.

1. Introduction

In the face of depleting fossil fuel reserves, escalating concerns over climate change, and the enduring repercussions of the COVID-19 pandemic, countries worldwide are grappling with a confluence of challenges. Among the industries significantly impacted is the manufacturing sector, particularly in furniture, construction, and packaging, where rising material costs and environmental consequences have become pressing issues. Traditional materials like medium-density boards, particle boards, concrete, timber, and plastics, along with their production processes, entail substantial costs due to the need for sophisticated equipment and extensive material transportation. Furthermore, the construction industry generates significant amounts of waste, adding to environmental degradation.

The disposal of construction waste presents multifaceted challenges, including pollution emissions, resource depletion, landfill overflow, and air contamination from incineration. These issues not only contribute to global energy consumption and greenhouse gas emissions but also underscore the urgent need for sustainable alternatives. For instance, the reliance on petroleum-derived glues and resins in particle and medium-density boards exacerbates both production costs and greenhouse gas emissions (Elsacker et al., 2020).

In response to these challenges, mycelium-based composites (MBCs) have emerged as promising biodegradable alternatives. MBCs utilize bio-composite waste, or substrate, bonded with dense mycelium to offer a sustainable solution to the growing demand for eco-friendly materials. While their potential is evident, the industrial application and research surrounding MBCs remain nascent. A deeper understanding of their production processes and properties is necessary to harness their full potential.

The development of MBCs is marked by vast possibilities due to the diversity of fungal species and substrate types, each contributing unique characteristics to the final material. However, critical knowledge gaps persist. Factors such as temperature, light, humidity, and CO2 concentration significantly influence the physical properties of MBCs but are not yet fully optimized. Moreover, the absence of standardized guidelines for fungal species selection and production parameters hinders consistent manufacturing practices and scalability. These gaps in the literature highlight the need for systematic exploration to address the technical and industrial challenges in this emerging field.

This review seeks to bridge these gaps by providing a detailed examination of the methods employed in the production of MBCs, including substrate selection, fungal species diversity, and key manufacturing processes. It evaluates both the benefits and limitations

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of MBCs while exploring their diverse applications in furniture manufacturing, construction, and packaging industries. Additionally, it highlights the unique ability of MBCs to address sustainability challenges through the innovative use of organic waste and renewable materials.

In summary, this review aims to offer valuable insights into the potential of MBCs by elucidating both their accomplishments and areas ripe for further exploration. By addressing critical gaps in knowledge and production practices, this paper seeks to catalyze ongoing research and innovation, nurturing the advancement of sustainable materials and paving the way for a more environmentally conscious future.

2. Methodology

2.1. Literature search strategy

To provide an overview of the potential of mycelium-based composites, a systematic literature search was conducted across major electronic databases, including PubMed, Scopus, and Google Scholar. The search included a range of keywords and combinations to ensure thorough coverage, such as "Mycelium-based composites," "Mycelium-bound composites," "Mycelium-based composite production techniques," "Mycelium-based composite innovations," "Mycelium-based composite limitations," "Mycelium-based composites environmental implications," "Mycelium-based composite economic benefits," "Mycelium-based composites in industry," "Mycelium-based composites application in healthcare," and "Mycelium-based composites post-processing." Using both "Mycelium-based" and "Mycelium-bound" ensured comprehensive coverage of the field's terminology and leading research groups.

2.2. Inclusion and exclusion criteria

Inclusion criteria included studies detailing the composition, production, treatments and post-processing stages of mycelium-based composites as well as its applications across several industries from healthcare to textile to manufacturing. It also included studies detailing the environmental benefits and challenges of mycelium-based composites.

Exclusion criteria comprised of duplicate articles, articles that were not written in English, contained irrelevant or insubstantial data and articles where the full text was inaccessible. Additionally, studies not directly related to the objectives of this review and ones lacking substantial information were excluded.

In summary, the literature search yielded a total of 115 references, with articles distributed across our key categories, including those discussing specific applications, environmental impacts, and recent innovations in mycelium-bound and mycelium-based composites.

3. Understanding mycelium and MBCs

Mycelium is the roots of the mushroom or the vegetative part of the fungus. The part of the mushroom that grows in the soil (roots) is called the mycelium while the part that grows above ground is called the fruiting body. Mycelium consists of highly dense fine fibrous filament called hyphae that contains proteins, glucans and chitin. Due to their unique metabolic and physiological behaviours, these organisms possess significant biotechnological potential (Madusanka et al., 2024). They offer robust, efficient, and economically viable solutions to current environmental issues. Mycelium can be grown on solid organic substrate such as wood sawdust, straw, hemp, wheat grains, coconut husk, rice hulls, wood chips, hay, etc. to obtain lightweight MBCs consisting of a three-dimensional interwoven network of fine fibrous filament-acting like a natural glue embedded in the substrate containing natural fibers (Manan et al., 2021).

Even though MBCs may not possess excellent structural performance characteristics, it can be successfully used for the following applications: fire resistance material, for aesthetic appearance, packaging materials, lightweight low-strength flexible materials, automotive industry, and furniture materials in art (Sydor et al., 2022b; Abhijith et al., 2018; Cerimi et al., 2019; Lingam et al., 2023). Some of the advantages of MBCs are the use of waste materials as the substrate, low energy requirement during production, near-net production, and MBCs can be easily recycled (Fairus et al., 2022; Walter and Gürsoy, 2022; Abdelhady et al., 2023; Mohseni et al., 2023). The major drawbacks of the MBCs are that they possess low tensile strength and are prone to biological corrosion (Lingam et al., 2023). The performance characteristics of the MBCs can be greatly improved by selecting the adequate substrate type and mixture, species of fungi and processing technology. The MBC materials should be easily manufactured, profitable, non-hazardous to humans and should have the required physical properties for actual industrial application. One of the difficulties in the production process is the selection of the appropriate fungal species and appropriate substrate, there are over 70 species that can be found to be used in the production of MBCs (Sydor et al., 2022a, 2022b). This combination of chosen species of fungi and substrate should support mycelium growth, produce the correct physical requirements of the bio-composite material, deactivate the fungus when required, repel insects, available, not contaminated, compatible with the substrate (Al-Qahtani et al., 2023). The two commonly used fungal species are *Ganoderma lucidum*, and *Pleurotus ostreatus* (commonly known as oyster mushrooms) (Lingam et al., 2023). These particular mushrooms fall under the category of white rot fungi or wood-decaying fungi, possessing the ability to break down plant components such as lignin (Blauwhoff et al., 2019). Due to its impressive biological efficiency, adaptability to a wide range of climates with minimal environmental control, rapid growth rate, and increased resilience to pesticides and diseases compared to other edible mushrooms, these mushrooms have become the most extensively cultivated at commercial level on a global scale (Zakil et al., 2022). Appels et al. (2019) reported that whereas Trametes multicolor produced a soft, smooth skin on the substrate's surface with a foam-like structure, Pleurotus ostreatus produced a material with a solid, rough surface when grown on rapeseed straw. According to Ziegler et al. (2016), the bending strength of Ganoderma lucidum cultivated on cotton biomass ranged from 7 to 26 kPa. The material that Pleurotus ostreatus produced was also stiffer than that of Ganoderma lucidum when grown on cellulose. Both mycelium-based materials' elasticity was significantly increased when dextrose was added to the growth media (Haneef et al., 2017). According to Aiduang et al. (2024), mycelium-based composites made from trimitic hyphal species like Geastrum fornicatum, Ganoderma williamsianum, and Lentinus sajor-caju showed better mechanical qualities than Schizophyllum commune, particularly in flexural strength, compressive strength, tensile strength, and impact strength. Additionally, when covering material surfaces, hydrophobic hyphae with thick, dense walls can improve physical qualities by lowering water absorption. Another important aspect affecting material qualities is the kind of substrate used for mycelium development. Fungal-based materials benefit from strain-hardening properties from substrates with unbroken natural fibers, which increase strength and prevent shear failure. Additionally, these fibers increase the Young's modulus of materials based on fungi and lessen cracking during shearing (Yang et al., 2017). Jones et al. (2018) reported a 300 % increase in the strength of pure MBCs when sand was added to wood chips. Additionally, composites grown on oak sawdust exhibited higher tensile strength compared to those grown on beech sawdust (Faruk et al., 2012). Cellulose, a constituent of plant cell walls, serves as a key carbon source for mycelium growth. Substrates with higher cellulose content provide sufficient nutrients, supporting more robust growth and potentially resulting in stronger composites. Similarly, hemicellulose, another component of plant cell walls, acts as a carbon source and contributes to mycelium growth and mechanical properties (Rigobello and Ayres, 2022). On the other hand, lignin, a complex polymer that provides structural support to plant cell walls, can hinder mycelium digestion due to its complexity. Substrates with lower lignin content are generally more favourable to mycelium growth (Andlar et al., 2018). The pH of the substrate is also crucial for mycelium growth, with most species successfully growing in a little acidic environment (pH 5–8). It is important to adjust the substrate pH to align with the optimal range for each mycelium species (Alaneme et al., 2023). The water-holding capacity of fungal-based mycelium depends largely on the substrate. For example, the water content of Trametes multicolor material ranged from 5.8 % to 7.2 % when grown on cotton and from 7.6 % to 9.6 % when grown on rapeseed straw (Appels et al., 2019). Antinori et al. (2020) conducted a study in which they cultivated Ganoderma lucidum in a potato dextrose broth, supplemented with alkali lignin and D-glucose to modify the hydrophobicity of the resulting fungal-based material. Since alkali lignin functions in the same way as original lignin and is broken down by the same enzymes, it was employed. Their results demonstrated that while lowering the amount of lignin in the growth medium encouraged quicker, more consistent mycelial growth and decreased the production of thin colonies, glucose increased the mycelia's porosity and susceptibility to moisture absorption. Furthermore, cold or heat pressing can greatly improve the structural characteristics of mycelium-based composites. Pressing helps to reposition fibers in a horizontal plane, enhances the material's density, and decreases porosity. This improves the material's overall strength by decreasing their thickness and increasing contact between fibers at overlapping locations (Manan et al., 2021). Further discussion of this process can be found in Section 6.

There are several methods available for making mycelial composites which are discussed in section 4. The general steps involved in the manufacturing of the mycelium-based composites are described here. Firstly, the substrate selection is important. Numerous authors (Lingam et al., 2023; Appels et al., 2019; Ghazvinian and Gürsoy, 2022) have claimed that the type of organic substrate used has an impact on the characteristics of the fungal skin that forms once the substrate is colonized. Thus, choosing the right substrate is essential when producing MBCs, particularly when product quality is of utmost importance. The substrate preparation is also essential, this depends on the type of substrate used. The substrates such as wood chips or sawdust, straw, rice husks, corn stalks, hemp, paper waste or cardboard, needs to be prepared by cutting it into smaller lengths of around 1–4 mm and soaking it in the water (Cai et al., 2023; Lingam et al., 2023; Sisti et al., 2021). Substrate of smaller length allows proper autoclaving and filling/occupying the mould for proper and homogenous growth of mycelium (Sisti et al., 2021). Another important factor is that the mycelium fibrous network should grow evenly throughout the mould or composite to obtain successful products and to reduce wastage. Soaking in water will adequately hydrate the substrate for the sterilization process (next process) to kill any spores and bacteria that may hinder the mycelium growth in the substrate. On the other hand, pre-hydrated substrate, spent substrate or liquid-based substrate may already have enough moisture content, eliminating the need for soaking (Leong et al., 2022; Schritt et al., 2021). Disinfecting or sterilizing the substrate is required to increase the activity and colonization rate of fungi and avoid contaminating the mycelium throughout the growth phase. The sterilization process can be obtained through chemical treatment, or through heat treatment at a predefined time and temperature. A temperature range of 110–125 °C and time duration of 15–30 min is employed in many research work (Appels et al., 2019; Elsacker et al., 2020). Then the sterilized substrate is sprayed with distilled water to moisten it and inoculated with mycelium spawn to initiate growth (Schritt et al., 2021). Two methods of inoculation employed and reported by many researchers (Jiang et al. (2014); Holt et al., 2012; Elsacker et al., 2020) are liquid-based inoculation and grain-based inoculation. The composite can be moulded into the desired shape after the initial growth which typically takes 7 days. The mould design and packing method is important as it affects the mechanical properties of the MBCs that depends on the mycelium growth, density, fiber orientation and dimension. The total production period of the composite may take around 35 to 45 days. Finally, the composite is either hot pressed, oven-dried or sun-dried to stop the mycelium growth and to end the production process (Jones et al., 2018; Alemu et al., 2022).

4. Techniques for MBCs production

The cultivation of mushrooms is very important in the production of MBCs as important bioactive compounds required can be successfully synthesized. This is greatly dependent on the cultivation technique. There are several techniques for the cultivation mycelium and the two most common used techniques are solid-state fermentation (SSF) and submerged fermentation (SmF) (Wang et al., 2023). Some of the advantages of the SSF process are low cost, disease-free, lower water and energy requirements, and higher volumetric productivity. The higher productivity stems from larger biomass and low product breakdown. The lower energy stems from less water used and the elimination of mechanical mixing. Moreover, better oxygen circulation is provided in the SSF process compared to the SmF process. The two main disadvantages of SSF over SmF are the difficulty in reproducibility of the required bioactive metabolites and purification of the final substrate after the whole SSF process. Another point to note is the long production time of SSF over SmF process. SmF is preferred over SSF in the industry due to better process parameter control. The SmF technology can extensively control important parameters such as agitation, temperature, pH and aeration. The temperature and pH is highly important as it affects mycelium growth rate, pellet and product formation which is not easy to control in SSF. SmF has a well-established technology, can be up-scaled to meet the industrial production demand easily and product recovery is simpler. One of the major disadvantages of the SmF process is the mass transfer of oxygen which may affect the enzymes produced in the final product.

One of the environmental and sustainability concerns in the cultivation and production of mycelium-based composites is the use of plastic moulds and more work is required to be done in this area to use and reuse sustainable mould materials and improve the technology to enhance sustainability (Holt et al., 2012; Pelletier et al., 2017; Jones et al., 2018; Lelivelt et al., 2015; Elsacker et al., 2020).

4.1. *Submerged fermentation*

In SmF, a liquid medium containing the required growth nutrients is used to grow the microorganisms. The SmF technique is cost-effective, takes less production time and reduces contamination when compared to SSF. The following parameters are absolutely important in the successful cultivation of the mycelium using SmF; pH, temperature, agitation and aeration time, carbon and nitrogen sources, and inoculum volume (Dudekula et al., 2020). The pH levels affect the changes in cell morphology and nutrient intake. A pH value of 5 generally produces a maximum mycelial composition of chitin, cellulose, and proteins. A pH value range of 3–5 would produce a good mycelial composition with a high production rate, and a pH value >5 would significantly reduces the production rate. Further, most mushrooms show optimal growth at a temperature range of 20 to 25 °C (Dudekula et al., 2020). Moreover, this can be seen in Table 2. However, there is no direct relation that exists showing the relation between the growth of mycelial biomass and temperature. For example, a study by Hwang et al. (Hwang et al., 2003) showed the maximum mycelial biomass was produced at a temperature of 30 °C.

Agitation and aeration rates affect the fermentation process as it will influence the microorganism's ability to absorb the oxygen for growth and survival which is dependent on the viscosity of the culture medium. Studies (Wang et al., 2023; Kim et al., 2003) have shown that higher aeration and agitation rates produced high-density mycelial biomass. On the other hand, another study (Cui et al., 2016) showed that low agitation and high aeration resulted in high-density mycelial biomass. It was found that an agitation rate of 200 rpm and aeration rate of 2 vvm is adequate to maintain the high dissolved oxygen in the media for optimum growth (Cui et al., 2016). A very high agitation rate increases the shear stress which reduces the mycelial biomass growth and disrupts the mycelium structure. A lower aeration rate may not be able to reduce the viscosity thereby blocking the media consumption and oxygen uptake.

The growth of mycelium in the SmF technique is dependent on the nitrogen and carbon sources. An addition of 5 % carbon sources and 0.5 % of nitrogen sources gives maximum mycelium growth (Dudekula et al., 2020). Some of the carbon sources used in the literature are glucose, fructose, maltose, saccharose, and lactose and nitrogen sources are calcium nitrate, yeast extract, peptone, tryptone, sodium nitrate, and ammonium sulfate (Kirsch et al., 2016).

Inoculum volume is important as it significantly affects mycelial biomass production. There have been several studies on this, however, the exact volume size is still under investigation. A study (Kirsch et al., 2016) was conducted using 0.5, 1.0, 2.0, 4.0, and 6.0 mL inoculum volume and the findings indicate that 6 mL produced the maximum mycelial biomass. Another study (Xu et al., 2011) shows that maximum mycelial biomass was induced at 2 % inoculum volume compared to lower growth at 0.5 % and 5 %. Moreover, (Lee et al., 2004) the highest mycelial biomass production was seen at 4 % of inoculum and with >4 % inoculum the mycelial biomass growth decreased. Fig. 1 shows the steps involved in submerged fermentation to obtain mycelial biomass. As seen in Table 2, the fungus is usually maintained on PDA slants and supplemented with seeding culture such as yeast extract (Kirsch et al., 2016), potato dextrose broth (Hsu et al., 2017), peptone, glucose, and vitamin B1 (Liu and Zhang, 2019). This is incubated for about 3–10 days as seen in Table 2 and the inoculum incubation temperature is 25 °C. In some cases where this needs to be stored for some additional time a storage temperature of 4 °C is maintained. After growth, the mycelium is transferred to the fermentation medium and incubated. The fermentation medium contains nitrogen and carbon sources to enhance the mycelium growth providing the required nutrients. Some common nitrogen and carbon sources are highlighted in Table 2. The incubation period generally lasts 2–12 days during the fermentation process at an agitation speed of around 100–160 rpm. Moreover, after growth, the inoculated mycelium can be in liquid or solid form when added to the fermentation medium as highlighted in Table 2. Finally, the substrate is dried in the incubator.

4.2. Solid-state fermentation

In SSF, a solid substrate is used to grow the microorganisms in the absence of free liquid. Fig. 2 shows the steps involved in solid-state fermentation to obtain mycelial biomass. As seen in Table 3, the fungus is usually maintained on PDA medium, spores are grown on PDA. The incubation time and temperature are usually in the range of 4–14 days and 25–28 °C, respectively. Next is in many cases (Wang et al., 2023; Hsu et al., 2022; Xin et al., 2022; Huang et al., 2010; Fakas et al., 2009; Hu et al., 2022; Lu et al., 2022; Liang et al., 2020), the initial mycelium is cut from the PDA plates and inoculated in a liquid medium under constant agitation rate of 120–160 rpm. The liquid medium contains the sources of carbon and nitrogen for mycelial growth. The next step involves substrate preparation (sizing, pH adjustment, nutrient addition) and transfer of inoculum to the substrate. After sizing reduction, the substrate is added with required nutrients such as soybean, red adlay, $Pb(NO_3)_2$ solutions, KNH solution, lime, sucrose, wheat bran juice, bran, $CaSO_4$, CaO, bean sprout juice and distilled water (Table 3) and autoclaved at 120–130 °C. The autoclave time is in the range of 30–50 min. Next, the substrate (cooled at room temperature) is inoculated with the previously sub-cultured mycelium and incubated (usually in the dark) for 10–21 days, however, can last up to 45–56 days depending on the mycelial biomass growth. The temperature during this time is maintained at 25–28 °C. Finally, the substrate is dried in the incubator. The water content is dependent on the fungi and the required bioactive metabolites such as hispidin production (Liang et al., 2020). The suitable pH range in the SSF process is 5.5 to 7. In the SSF method, pH is very difficult to measure and control. This is because of the very low water content (lack of free water) and the nature of the solid substrate. One of the major environmental concerns of SSF is the solid waste generation including unused biomass and spent mushroom substrates. Suitable waste management approaches are necessary to minimize

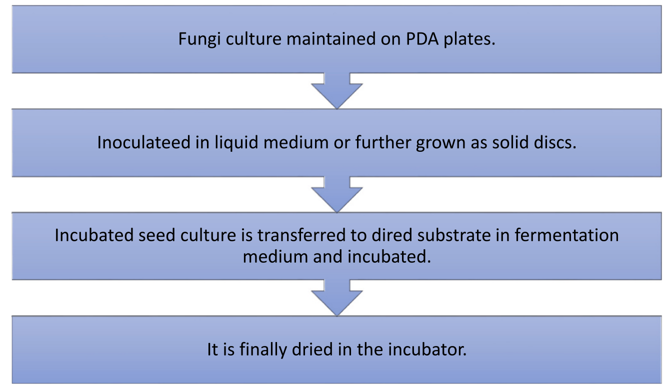

Fig. 2. Solid-state fermentation process.

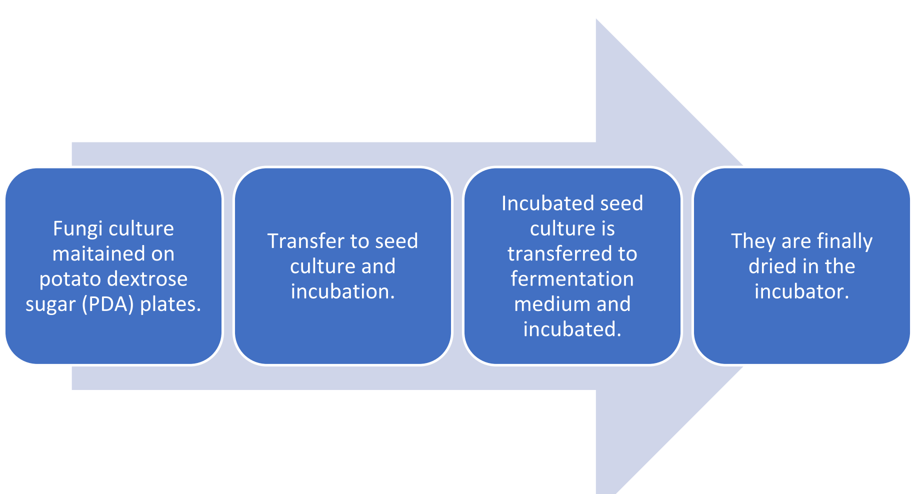

Fig. 1. A summary of the submerged fermentation process.

environmental impact such as reusing the substrate for the new cultivation cycle of mushrooms, soil amendment and biofertilizer, renewable energy production, animal feed, and pollution bioremediation (Leong et al., 2022).

4.3. Plastic bag method

This method involves the preparation of the substrate. The substrate is cut to the required length of approximately 2–5 cm for easy mixing and packing into the plastic bag and soaked in water for about 24 h to hydrate. The substrate can be given hot water treatment by boiling it at 70–80 °C to remove any containment and allow easy use of cellulose by the fungi. Finally, the substrate is dried by squeezing the water at room temperature and the required nutrients are added such as wheat bran if required. Some common substrates used are paddy straw, wheat straw, sawdust, bagasse, etc. However, the comparability of the substrate with the fungal species is important.

The plastic bag is prepared (normally 40 cm × 20 cm in size) by punching 5 mm holes at a distance of about 10 cm between holes. This is to allow for good ventilation during the process. The plastic bags are filled with the substrate and spawn are sprinkled evenly on top. Four to five layers of the same (substrate and spawn) can be filled in the plastic bag and the bag is closed making a round shape. The bags should be placed indoors avoiding direct sunlight and heat. The spawn can be prepared using the pure mushroom tissue cultured on PDA medium as used in the SmF and SSF process. Afrida et al. (Afrida, Willard, Lukman, and Tamai, 2019) cultivated mushrooms using sawdust, bran, lime and spawn. One bag of spawn (12 × 25 cm in size) was used to prepare 50 bags of mycelium of the same size containing 45 kg of sawdust, 2 kg of bran and 0.5 kg of lime. The spawn were grown on rice, corn and a mixture of rice and corn. The spawn production on corn was preferred for *P. ostreatus* as it resulted in thick mycelium, fast growth and good yield. In another study (Tesfay et al., 2020), oyster mushroom spawn was cultured using sorghum, wheat bran and gypsum that was thoroughly mixed maintaining 55–60 % moisture content. A thick mycelium growth was observed after 15 days of inoculation at 25 °C. In the same study, waste paper and corn stalks were used as substrate (size = 3–5 cm). The substrate was soaked in water for 24 h and then hot water was boiled at 60 °C for 30 mins. After cooling to room temperature, it was removed and dried to maintain a moisture level of 65–75 %. The substrate and spawn were packed in sterile plastic bags (with holes for proper ventilation) and kept inside in the dark at 25 °C. There is no mention of reusing the plastic bags in the study (Tesfay et al., 2020), however, the use of waste paper supplemented with wheat bran and corn stalks offers solid waste management in an eco-friendly manner. The waste paper contains active carbon sources (cellulose, lignin and hemicellulose) serving as a basal medium resulting in higher biological efficiency and yield. One of the drawbacks of this technique is the use of plastic bags. It is recommended to use the plastic bags several times before discarding. Another option is to use glass bottles instead of plastic ones (Tesfay et al., 2020). The glass bottle can be closed using unsterilized cotton or old newspaper for air circulation.

5. Recent innovations in SSF and SmF

One of the recent innovations is the development of a low-cost solid-state cultivation bioreactor that can be used in the SSF and SmF processes. The current commercial bioreactors present a lack of scaling-up successful bench-scale apparatuses and online monitoring/controlling of process variables (Henrique et al., 2022). Manan and Webb (2020) designed a six-layer bioreactor consisting of six circular perforated trays to be used in the SSF of *Aspergillus oryzae* and *Aspergillus awamori* species as shown in Fig. 3. The innovative bioreactor was equipped with an automatic oxygen and carbon dioxide gas analyser to monitor O_2 and CO_2 consumption. Furthermore, a temperature monitor system was also installed. The bioreactor system designed and tested can possibly be used for large-scale processes, though some design optimization is further required such as the number of trays and height-to-diameter ratio required. An automatic gas concentration monitoring system in a packed-bed SSF bioreactor was designed and studied as shown in Fig. 4 (Henrique et al., 2022). SSF cultivation of *Myceliophthora thermophile* in wheat bran and bagasse was studied with this automated system. Several variables were monitored and optimized such as gas removal, inlet air flow rate, aeration, and metabolites production for large-scale production. Their research will help to significantly develop the aeration process in the packed-bed bioreactors, reducing the air pumping costs and enhancing the production of required metabolites. Zhang et al. (2023a) studied the performance of several bioreactors used in submerged fermentation namely, panel bioreactor, stirred-tank bioreactor, and fluidized bed bioreactor configurations. It was found that the panel bioreactor produced floccose and larger pellets, and the stirred-tank bioreactor produced compact elliptical pellets. The stirred-tank bioreactor was equipped with a mixing impellor and produced the highest volumetric biomass. It was clearly noted that different designs of

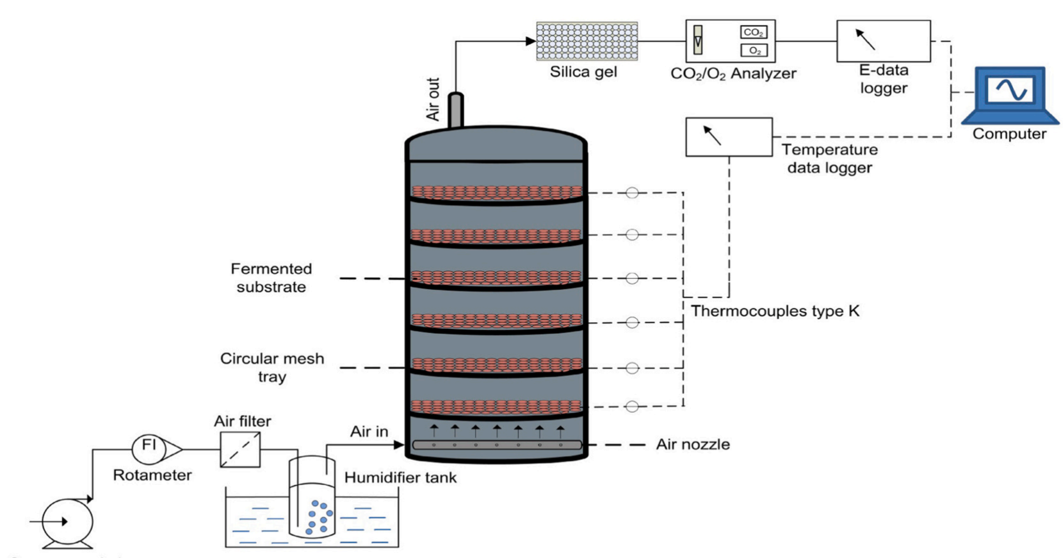

Fig. 3. Multi-stacked circular tray solid-state bioreactor (Manan and Webb, 2020).

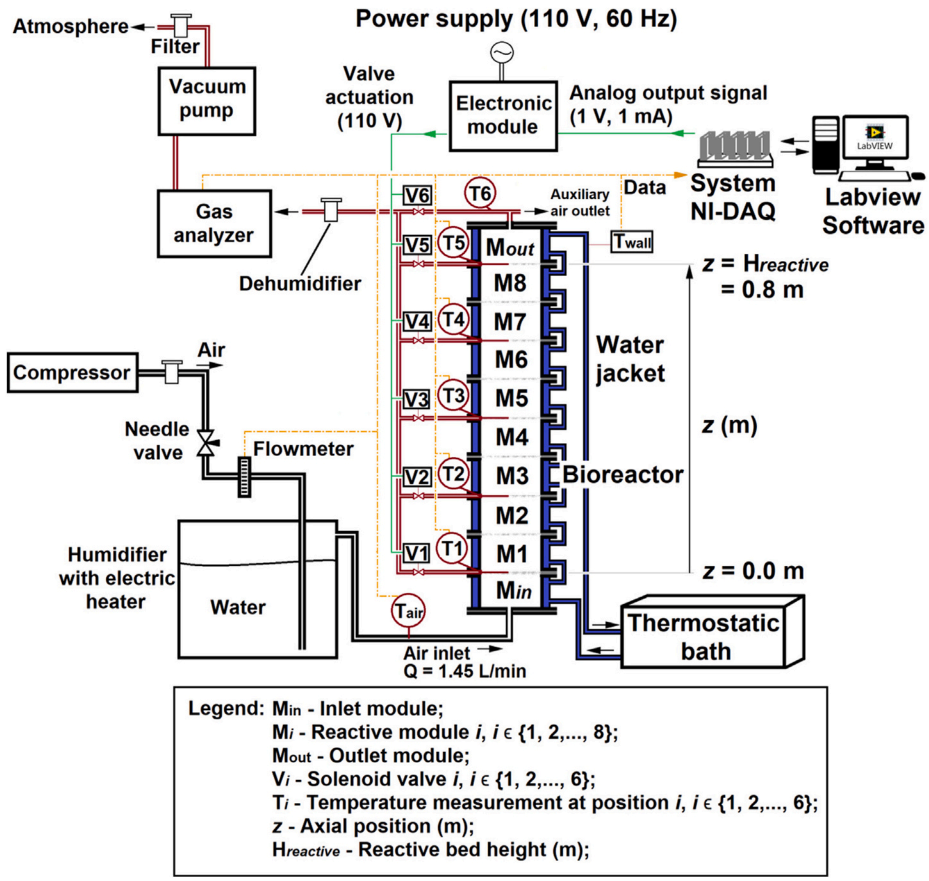

Fig. 4. Solid-state bioreactor (Henrique et al., 2022).

bioreactors affected the fungal pellet morphology and metabolic of interest and bioreactor designs are essential in the mycelium fermentation process.

6. Treatments and post-processing

The properties of MBCs depend on the species of fungi, substrate used, growing environment and post-processing. There are many post-processing treatments available such as heat treatment, drying, and chemical treatments, used to enhance the properties of mycelium-based composites. Depending on the end-use of the composites, different types of coatings can be applied, weather-proofing with natural polymer or natural oil can be used, and bioresin impregnation can be applied. Jiang et al. (2014) studied the vacuum infusion of MBCs with natural resins to improve the stiffness and flexural strength of the composites. The sandwich bio-composite structures were subjected to thermal pressing (to impregnate the resin) and oven drying. Jiang et al. (2017) studied the mechanical properties of 2-ply reinforced MBCs. The following woven natural textile skin reinforcements were used; Biotex Jute, Biotex Flax and BioMid Cellulose. The thickness of the skin ply was 0.53–1.75 mm and the main core thickness was in the range of 21.9–24.2 mm. The skin reinforcement was applied by resin infusion and thermal pressing followed by oven drying. The ultimate strength and yield stress of the flax skin reinforcement was twice that of the other two skin reinforcements. Further, the stiffness property was not dependent on the different types of skin reinforcements but on the main core of the sandwich structure. Nussbaumer et al. (2023) produced MBCs utilizing beech sawdust that was subjected to hot pressing. The composites were produced in disk shapes of approximately 8 cm diameter and maximum thicknesses of 12.4 mm and were hot pressed at 120 °C with an applied load of 100 kN that was withheld for 50 min. The densities of the MBCs almost doubled as a result of hot pressing with tensile strength ranging from 130 kPa to 1.55 MPa. Liu et al. (2019) investigated the impact of pressing temperatures (160, 180, and 200 °C) on the physical, mechanical, and thermal properties of composites. Results indicated that increasing the pressing temperature significantly enhanced most properties due to improved interfacial bonding. However, while higher temperatures slightly affected thermal decomposition resistance, the overall resistance improved with increasing temperatures. The optimal conditions were achieved at 200 °C, where the flexural and internal bonding strength of the composites was comparable to non-load-bearing fibreboard. Furthermore, Sakunwongwiriya et al. (2024) studied the mechanical properties and water absorption of MBCs with different coating solutions, mainly, wet starch, chitosan and epoxy resin. The results showed that MBC coated with chitosan achieved the highest compressive strength of 1.46 MPa and while the MBC coated with epoxy resin exhibited the highest flexural strength and least water absorbent as the resin is hydrophobic. Elsacker et al. (2021) showed that using heat pressing as a post-treatment process improved the flexural strength of MBCs by 200 % when compared to unpressed samples. Further, significant improvement in tensile properties were observed in the heat pressed samples. This post processing ensured that the MBCs remained weather proof and durable. Table 4 below gives the property enhancement through the post-processing of MBCs. It can be seen that the most common post-processing treatments are the heat treatment process and heat pressing process as they seem to influence the mechanical properties significantly.

7. Current applications of MBCs

In terms of manufacturability, there are not many companies that are producing MBCs at large within different sectors such as construction, packaging, medicine or biomedical and textile. However, much research has been undertaken to study the various potential uses of MBCs within these sectors or industries and are quite promising. Over the past decade, mycelium materials have seen a rise in companies and patents. Notable among them is Ecovative (Ecovative - Mycelium Technology | Sustainable and Biodegradable Material, n.d.), specializing in MBC materials for protective packaging and insulation, serving as alternatives to traditional polystyrene. MycoWorks (MycoWorks, *n.d.*), explores mycelium composites, with early work on MBC bricks led by founder Philip Ross. Presently, MycoWorks focuses on developing MBC leather substitutes. Mogu (muvobit, n.d.), a significant player in MBCs, focuses on sustainable alternatives for interior and product design, particularly floors and acoustic tiles. Collaborations with commercial and academic partners are evident. Despite continuous innovation releases on websites and social media, the literature review highlights that associated academic publications lack essential data, likely due to commercial considerations (Attias et al., 2020).

7.1. Construction

The depletion of natural resources and the increased concerns about environmental pollution have sparked a growing interest in the production of more sustainable materials. One industry facing great challenge is the construction industry which heavily relies on fossil fuels and raw materials. A possible solution is to adopt naturally improved materials, created by cultivating mycelium forming fine dense fibrous network on natural fibers abundant in cellulose, hemicellulose, and lignin. Additionally, this MBCs production recycles organic waste materials and is biodegradable after its life cycle (can be disintegrated into the soil easily), a process aligned with the principles of a circular economy (Elsacker et al., 2020). Several studies given in Table 1 show significant contributions towards the environment and sustainability by reducing, reusing, recycling, and recovering the amount of waste generated from building construction and demolition. Table 1 highlights the current literature on the successful and possible use of mycelium-based biodegradable materials that can be used by the construction industry to replace traditional construction materials.

Many applications are found to be used in the area of insulating material, packaging of small consumer goods and acoustic and sustainable architecture applications as it requires low mechanical strength. More research and development are required in the production of mycelium-based composites for high-strength applications. However, several articles have shown promising mechanical properties and future work is required to further improve the mechanical properties of the MBCs. It can be seen that the most common substrates used are sawdust, straw and bagasse due to their lignocellulosic content and their compatibility with mycelium growth leading to higher mechanical properties. Further, higher mycelium growth results in high compressive strength as well.

The prevalent approach involves crafting mycelium building blocks that are then assembled into larger structures. However, this application often depends on substructures and is geometrically restrictive due to mycelium's inherent properties, allowing only for structures in compression. Studies have also investigated monolithic mycelium constructions, but these systems necessitate either substantial scaffolding or extensive reinforcement systems, which, in most instances, assume the structural functions, relegating the mycelium to a surface finish rather than a load-bearing material (Sydor et al., 2022a, 2022b). Some of the well-known MBC's structures developed across the world are the Gowing Pavilion in Netherlands (About The Growing Pavilion, *n.d.*), My-Co Space in Germany (My-Co Space—V. meer, *n.d.*) and Monolito Micelio in USA (El Monolito Micelio—Jonathan Dessi-Olive, *n.d.*).

MycoTile (African Stories, The Circular Economy Opportunity: MycoTile, *n.d.*) a company based in Kenya, produces alternative building materials using agricultural waste and fungal mycelium. Their products are cheaper, more sustainable, and have better performance than traditional construction materials. They use a carbon negative process to create products such as ceiling panels, wall insulation, construction blocks, and furniture. Partnering with small scale farmers the company is able to source their raw materials and create a circular economy. MycoTile aims to revolutionize the construction industry with their innovative and eco-friendly solutions.

Researchers have also explored the development and assessment of dense mycelium-bound composites (DMCs) as a potential substitute for traditional particleboards. In a study by Chan et al. (Chan et al., 2021), *Ganoderma lucidum* mycelium was employed to bind agricultural waste products like sawdust and empty fruit bunches into a composite material. The resulting MBC underwent testing under tropical weathering conditions, evaluating its mechanical properties in flexure, tension, and compression. The study revealed that weathering significantly diminished the material's strength and rigidity, but applying a protective coating could alleviate some of these effects. The authors suggested enhancing the material's consistency and performance by modifying the production process. Özdemir et al. (Özdemir et al., 2022) created wood-veneer-reinforced MBC for sustainable building components. The authors propose a novel bio-based material system that combines the advantages of mycelium and wood veneer and present a custom robotic fabrication process that integrates continuous wood fibers into the mycelial matrix as reinforcement. Zhang et al. (Zhang et al., 2023b) used different sizes of poplar or birch sawdust as substrates for *Trametes versicolor*, a white-rot fungus, to produce MBCs with high porosity and low density. They investigated the morphological, biological, and physicochemical properties of the MBCs, as well as their mechanical, cushioning, thermal insulation, and hydrophobic properties. It was found that the MBCs had comparable and better performance than expanded polystyrene (EPS), petroleum-based plastic, and demonstrated that the MBC have better thermal insulation than wood and EPS making MBC a promising material for manufacture of sustainable insulation materials.

Furthermore, MBCs possess outstanding sound-absorbing properties. Their porous structure effectively traps and dissipates sound waves, reducing noise levels in environments such as recording studios, offices, and homes, preventing sound from passing through walls, ceilings, and floors, thereby enhancing privacy and comfort. Various studies have evaluated the sound absorption and acoustic insulation properties of MBCs. Walter and Gürsoy (2022) produced MBCs on wastepaper substrates for biodegradable sound-absorbing materials. They cultivated MBCs using Pleurotus ostreatus on substrates like cardboard, office paper, and newsprint. Impedance tube tests (ASTM E1050–12 standard) measured the sound absorption coefficients of various MBCs. The results showed that fine cardboard (FCL) samples exhibited the best absorption in mid-range frequencies (500 Hz to 2 kHz), while shredded cardboard (SCH) samples performed best at high frequencies (2 kHz to 6.4 kHz), confirming their sound absorption capabilities. Pelletier et al. (2019) explored the acoustic properties of a novel renewable biopolymer made entirely from pure fungal mycelium. Derived from the mycelium of *Ganoderma* fungus, the biopolymer was grown under specific conditions (30–35 °C, high CO_2) to prevent fruiting body formation, resulting in a pure mycelium structure free from the substrate, which yielded a closed-cell foam board. The acoustic properties of this mycological foam were tested using an impedance tube, focusing on sound absorption over the frequency range of 350 Hz to 4 kHz. The material demonstrated strong low-frequency absorption, outperforming traditional materials like ceiling tiles and cork at frequencies below 1500 Hz. These research findings shows that sound can be successfully attenuated by the peculiar structure of mycelium, which is composed of an interconnected network of hyphae. Because of this, it's a great option for acoustic insulation. Further, green building practices are supported by the use of composites made of mycelium for acoustic insulation. It lessens dependency on artificial materials, which frequently have a negative influence on the environment and are not biodegradable.

Commercial MBCs currently available in the market are generally

Table 1
Mycelium-based composites with different fungi and substrates.

Fungal species	Substrate	Product/Application	Results	Ref.
Pleurotus ostreatus	Waste cardboard	Acoustic panels.	The MBCs were successfully used to replace the petrochemical-based materials within the architectural industry for sound-absorbing properties. The MBCs performed well structurally and acoustically.	Walter and Gürsoy (2022)
Pleurotus ostreatus	Bagasse, Coconut husk, Juncao grass, Mixture of coconut husk and bagasse. Rice husk was added to all for mycelium nutrients.	Insulating material, Packaging of small consumer goods, False ceiling.	Juncao grass - flexural strength = 399.39 kPa, compressive strength = 78.34 kPa. Bagasse MBC showed good fire resistance properties. These MBCs can successfully replace non-biodegradable and high-cost products such as Styrofoam, asbestos ceiling tiles, blown mineral fiber, polystyrene beads and urea formaldehyde foam.	Lingam et al. (2023)
Mycelium growing kit was used.	Hemp	Modular and interlocking components used in sustainable architectural application. Do not require the use of fasteners.	Hemp substrate showed very good stiffness and can be easily assembled and disassembled. This MBC can replaced the use of expansive materials such as aluminum, copper, etc. used for architectural applications. One such example is the use of MBC material to build the "MycoTree"" at the Seoul Biennale of Architecture and Urbanism.	Heisel et al. (2017)
Pleurotus ostreatus	Waste cardboard	3D-printed MBCs.	They work showed successful production of MBCs using 3D printing that can eliminate the wastage of the mould if the moulds are not reusable or recyclable. Further, this technique can print intricate and complex geometries.	Mohseni et al. (2023)
Ganoderma lucidum	Rice straw, Wheat straw, Corn straw	Thermal insulation material, Construction materials.	The manufactured MBCs have promising thermal degradation and fire resistance properties. Can successfully replace polyurethane foam as commercial insulation material. Rice and wheat straw MBCs compressive strength = 6.4 MPa. This is equivalent to clay brick and higher than EPS panel.	Cai et al. (2023)
Fomitopsis Pinicola, Agaricus bisporus, Trametes versicolor	Sawdust, Bamboo, Wood shavings	Construction materials	Maximum tensile strength achieved = 0.49 MPa. Recommendation is to further develop MBCs to improve its mechanical properties to incorporate it in construction industries.	Bagheriehnajjar et al. (2023)
Trametes versicolor	Poplar and birch Sawdust	Thermal insulation material, Packaging, Construction materials	Excellent thermal insulating properties were found, better than expanded polystyrene (EPS). Can successfully replace plastics used in packaging. Maximum compressive strength archived = 0.5 MPa surpassing the ASTM standard for EPS.	Zhang et al. (2023b)
Pleurotus ostreatus, Trametes multicolor	Straw, Sawdust, Cotton	Construction materials and packaging. Cold-pressed MBCs qualify to be foam-like material and heat-pressed MBCs produced qualify to cork and wood-like performance.	Tensile strength = 0.24 MPa, Flexural strength = 0.87 MPa, The MBCs produced are lighter than some wood composites such as OSB wood composite boards and medium-density fiberboard. Straw-based MBC was found to be stiffer than cotton-based MBC.	Appels et al. (2019)
Lentinula edodes	Peach palm (*Bactris gasipaes*) residues	Foam like structures and can replace polystyrene.	Compressive strength = 223 kPa. The main disadvantage of the MBCs, compared to polystyrene, is their high and fast water absorption.	Lima et al. (2020)
Trametes versicolor	Hemp, Flax, Flax waste, Softwood, Straw	Thermal insulation foam, Construction materials	Can replace fossil-based materials. The produced MBCs showed better insulation properties compared to traditional insulation materials such as rock wool and glass wool. The MBCs produced also had very low water absorption properties. The MBCs achieved a compressive strength of 1.18 MPa.	Elsacker et al. (2019)
Pleurotus ostreatus	Oak sawdust, Straw	Construction materials in architecture, engineering, and the construction industry such as compressive structural forms.	Maximum compressive strength = 498 kPa. The designed MBCs can successfully bear light loads. Further, the growth time is very important as longer growth time had a negative effect on the compressive strength.	Ghazvinian and Gürsoy (2022)
Ganoderma lucidum	Cotton-based	Packaging material, Foam core of sandwich board	The produced MBCs exceeded the characteristics of polystyrene foam. The strength of MBCs can be increased with decreasing moisture content.	Holt et al. (2012)

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Table 1 (*continued*)

Fungal species	Substrate	Product/Application	Results	Ref.
Trametes versicolor, Pleurotus Ostreatus	Hemp, Wood chips	Insulating foam, Construction board	Hemp with *Trametes versicolor* had the highest compressive strength and good thermal insulation.	Lelivelt et al. (2015)
Pleurotus ostreatus, Lentinula edodes, Ganoderma lucidum	Wood shavings, Straw	Panel board	The prepared MBCs is suitable to be used as panel boards and it is very important to follow the right process to avoid other species growth apart from the chosen mycelium fungi.	González and Diez (2016)
Irpex lacteus	Sawdust pulp, Millet grain, Wheat bran	Foam can replace polymeric thermal foams.	The produced MBCs have similar characteristics such as compressive strength, elastic moduli and thermal conductivity to polymeric thermal foams	Yang et al. (2017)
Trametes sp., *Schizo-phyllum commune*	Fruit/ vegetable peels, Agricultural waste	Compressed boards for packaging material, furniture, and footwear.	The produced MBCs has good mechanical properties with the help of increased nutrition supply after the homogenization process.	Karana et al. (2018)
Pleurotus ostreatus	Wheat bran, Bagasse, Sawdust	Insulation, Packaging material, Furniture, Wall paneling,	Compressive strength = 6500 kPa. This is almost 5 times more than the compressive strength of polystyrene packaging material.	Joshi et al. (2020)
Trametes versicolor	Hardwood Chips, Hemp shives	Building materials	Compressive strength = 520 kPa. The mechanical strength of the manufactured MBCs were equivalent to commercially produced hemp magnesium oxychloride concrete, cemented wood wool panel.	Zimele et al. (2020)
Ganoderma lucidum	Rapeseed straw	Wall insulation	Compressive strength = 845 kPa which is comparable to petroleum-derived synthetic EPS. Further, the MBC has good thermal conductivity and dimensional stability.	Gauvin and Vette (2020)
Pleurotus ostreatus, Volvariella, Polyporus squamosus	Hemp fiber, Wood chips	Design and architecture	Compressive strength = 452 kPa and flexural strength = 397 kPa. These are comparable to Ecovative grown tile.	Etinosa (2019)
Pleurotus ostreatus	Cotton seed hulls	Building boards	The addition of 5 % sbr latex and silane coupling agent improved the growth and bonding resulting in improved specific strength.	He et al. (2014)
Pleurotus Ostreatus, Ganoderma lucidum	Cellulose, Potato-dextrose broth	Fibrous mycelium film	The potato-dextrose broth is added to the substrate to improve the MBC stiffness for the successful application.	Haneef, Ceseracciu, Canale, Bayer, Heredia-Guerrero & Athanassiou (2017)
Trametes versicolor	Rice hulls, Glass fines, Wheat grains	Fire safe mycelium biocomposites	The MBCs had longer flash time, less Co_2 and smoke emissions, and low thermal conductivity.	Jones et al. (2018)

used as insulating panels, packaging materials, interior design applications and acoustic tiles. These products are manufactured by Ecovative Design, Krown Design and MOGU. The MBC acoustic panels have a noise-reduction coefficient of 0.53 and are sold as a replacement for traditional acoustical ceiling tiles. Moreover, these MBC acoustic panels also have very good thermal insulation (0.05 W/mK) and are used as a replacement for polyurethane (0.006–0.18 W/mK) and polystyrene foams (0.04 W/mK) (Elsacker et al., 2020; Walter and Gürsoy, 2022; Cai et al., 2023; Zhang et al., 2023b; Lima et al., 2020; Elsacker et al., 2019). Heisel et al. (2017) in Table 1 also show that MBCs can be used as load-bearing mycelium building blocks with successful construction of "MycoTree" at the Seoul Biennale of Architecture and Urbanism. At present, these load-bearing mycelium building blocks cannot compete with commercial high/average compressive strength materials such as concrete and brick masonry.

The mushroom industry has shown great interest and potential towards producing high-quality MBCs to be used in various sectors. A company CNC Exotic Mushrooms recently announced a partnership with Ecovative to design and manufacture mycelium materials for the European market (Deeg et al., 2017), the spawn producer Mycelia and Grimm and Wösten are open to collaborations with design and construction sectors to aid in the production and application of MBCs using edible mushrooms (Grimm and Wösten, 2018). Indeed, more collaboration is required between the mushroom industry, construction industry, the design industry and education sector to fill in the knowledge gap from different sectors and develop industry-ready sustainable and innovative MBC products for a wide range of applications.

7.2. *Biomedical*

MBC materials transcend traditional uses, particularly in medicine, offering a sustainable and potentially ground-breaking solution for medical applications. Utilizing mycelium's natural bonding properties, these composites facilitate the development of environmentally friendly and biocompatible materials. In the medical sector, they may be employed for innovative purposes like crafting biodegradable wound dressings, designing drug delivery systems, or creating tissue engineering scaffolds. This exploration aligns with the rising interest in sustainable materials advancing healthcare while minimizing environmental impact. Companies and researchers actively investigate MBCs potential to address medical challenges and promote sustainable practices in the healthcare industry.

Research confirms the biomedical effectiveness of chitin and chitosan in advancing wound treatment and understanding their healing mechanisms. Jones et al. (Jones et al., 2020b), highlights their significant role in the four stages of wound healing: hemostasis, inflammation, proliferation, and remodelling. In the first stage, chitosan enhances clotting by forming a coagulum with red blood cells. The second stage involves macrophages consuming dead cells, attracting fibroblasts, and supporting skin and blood vessel replacement; chitin and chitosan aid

Table 2
Inoculum and fermentation conditions for mycelium production via SmF.

Fungal species	Inoculum	Fermentation process	Result	Ref.
Pleurotus albidus	Fungi culture was maintained on potato dextrose agar (PDA) medium incubated in the dark for 8 days at 25 °C. Later stored at 4 °C. Seeding culture medium - 0.5 % yeast extract.	An aqueous homogenate of mycelium (AMC) was prepared using distilled water in a blender. Different volumes (0.5, 1.0, 2.0, 4.0, and 6.0 mL) of AMC was added to the standard fermentation medium of: $MgSO_4·7H_2O$ (0.5 gL^{-1}), KH_2PO_4(1.0 gL^{-1}), Peptone (10.0 gL^{-1}), Glucose (20.0 gL^{-1}). PH = 6.0. Incubation time = 5 days at 25 °C. Agitation rate = 150 rpm.	Successful production of mycelial biomass using *Pleurotus albidus*.	Kirsch et al. (2016)
Ganoderma formosanum	Fungi culture was maintained on PDA medium incubated for 10 days at 25 °C. Liquid seeding culture medium - Potato dextrose broth Agitation rate = 120 rpm Incubation time = 7 days	$MgSO_4·7H_2O$, KH_2PO_4, Glucose, Yeast extract, Vitamin B1. Incubation time = 9 days at 25 °C. Agitation rate = 120 rpm. Inoculum volume = 10 %.	Successful production of mycelial biomass.	Hsu et al. (2017)
Ganoderma lucidum	Fungi culture maintained on PDA medium incubated for 7 days at 25 °C and stored at 4 °C. Liquid seeding culture medium: Peptone, Glucose, Yeast extract, Vitamin B1, KH_2PO_4, $MgSO_4·7H_2O$. Agitation rate = 160 rpm Incubation time = 4 days	Peptone, Glucose, Yeast extract, KH_2PO_4, $MgSO_4·7H_2O$, Rice bran, Wheat bran, Corn flour, Soybean meal. Agitation rate = 160 rpm Incubation time = 2 days Inoculation volume = 5 mL.	Successful production of mycelial biomass.	Liu and Zhang (2019)
Ganoderma lucidum	PDA medium incubated at 25 °C. Incubation time is not specified.	After growth, mycelium disks were prepared from the previously sub-cultured (PDA) and added to the standard fermentation medium of: Liquid medium (125 mL), Peptone, Yeast extract, Glucose. PH = 6.0. Incubation time = 12 days at 25 °C. Agitation rate = 0 and 120 rpm.	Cultivation under agitation showed higher mycelial biomass growth.	Pessoa et al. (2023)
Tuber borchii	PDA plate incubated for 28 days at 25 °C	After growth, mycelium cutter square (20 mm × 20 mm) were prepared from the previously sub-cultured (PDA) and added to the standard fermentation medium of: mL Erlenmeyer flasks containing 100 mL of seed media with the following composition: 0.02 % $MgSO_4•7H_2O$, 0.5 % glucose, 0.1 % peptone, 0.1 % yeast extract, 0.02 % KH_2PO_4, Vitamin B1. PH = 7.0. Incubation time = 21 days at 25 °C. Agitation rate = 100 rpm.	Various carbon and nitrogen sources were analyzed for their performance and the most suitable and effective was found to be sucrose (80 g/L) and yeast extract (20 g/L), respectively, which produced maximum mycelial biomass growth.	Chen et al. (2023)
Fusarium equiseti	PDA plate incubated for 3 days at 25 °C with chloramphenicol as seed culture medium. Later stored at 4 °C.	A spore suspension was prepared from the previously sub-cultured (PDA) using distilled water. A volume of 1 mL spore suspension was added to five different liquid fermentation medium of: 1) Potato dextrose containing 20 g glucose, 200 g peeled potato; 2) Potato sucrose liquid medium containing 20 g sucrose, 200 g peeled potato; 3) Sabouraud Dextrose Agar with yeast extract containing 10 g peptone, 40 g glucose, 10 g yeast powder; 4) Czapek–Dox containing 3 g $NaNO_3$, 30 g sucrose, 0.5 g KCl, 0.01 g FeSO, 1 g K_2HPO_3, 0.5 g	The submerged culture conditions and optimized medium are the main control factors in the production of high quality mycelial biomass. The biomass growth was higher in the potato sucrose liquid medium when compared to other medium.	Zhao et al. (2023)

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Table 2 (*continued*)

Fungal species	Inoculum	Fermentation process	Result	Ref.
		$MgSO_4.7H_2O$; 5) Glucose yeast extract containing 20 g yeast powder, 40 g glucose. All sets had the same variables as below: PH = 7.0. Incubation time = 8 days at 28 °C. Agitation rate = 150 rpm.		

macrophages in this phase. In the third stage, chitosan promotes IL-8 production in fibroblasts, crucial for dermis reformation and extracellular matrix synthesis. Finally, keratinocytes, essential in the last stage, facilitated by chitosan, contribute to epidermis reformation in wound healing.

In another study by Antinori et al. (2021), presented the use of mycelia, as self-growing bio-composites that mimic the extracellular matrix of human body tissues, ideal as tissue engineering bio-scaffolds. The authors grew and characterized the mycelia of two edible fungi, *Pleurotus ostreatus* and *Ganoderma lucidum*, and investigated their biocompatibility and interaction with primary human dermal fibroblasts. The results showed that the mycelia had suitable morphology, porosity, chemical composition, hydrodynamics and mechanical properties for cell attachment and growth, and that they do not induce cytotoxicity or inflammation, hence making them promising candidates as all-natural and low-cost bio-scaffolds for tissue engineering applications.

7.3. Packaging

Utilizing MBCs material shows significant promise as a potential alternative to polystyrene in packaging applications. By utilizing mycelium, the fibrous structure of fungi, these composites present a sustainable and eco-friendly alternative to conventional packaging materials. Mycelium's inherent bonding properties facilitate the development of robust and biodegradable packaging solutions. Pioneering efforts by companies like Ecovative showcase the use of mycelium in protective packaging, providing a viable substitute for conventional materials like polystyrene. This innovative approach not only addresses environmental concerns linked to traditional packaging but also underscores the potential of MBCs to contribute significantly to a more sustainable and environmentally conscious packaging industry.

In a study by Sivaprasad et al. (Sivaprasad et al., 2021), sawdust-coir pith substrate was employed as the matrix, with oyster mushroom mycelia serving as reinforcement. This resulted in a biodegradable, renewable, and cost-effective material. The researchers conducted assessments, comparing properties such as biodegradability, compressive strength, acoustic performance, thermal conductivity, and water absorption with EPS. Conclusively, the MBCs exhibited superior mechanical and fire-retardant properties compared to EPS, suggesting its viability as a sustainable packaging material.

M2Enviro, the sustainability division of South African bioceutical company M2Bio Sciences, is set to introduce Hempcelium™, an eco-friendly packaging solution crafted from a blend of hemp and mycelium, aiming to replace environmentally harmful polystyrene. Undergoing rigorous material qualification testing to attain a Technology Readiness Level (TRL) of 8 (Robinson, 2022), the innovative Hempcelium™ addresses diverse customer needs through a pioneering method developed by the M2Enviro team. Localizing its supply chain and ensuring comprehensive in-house production, M2Enviro starts by assessing customer packaging requirements and utilizing FDM 3D Printing technology to create in-house moulds. Filled with proprietary hemp substrate, these moulds undergo a growth phase followed by sterilization, preserving product lifespan and creating a lightweight, biodegradable composite. This meticulous approach caters to various customer demands for strength, flexibility, and durability, marking Hempcelium™ as a promising sustainable alternative in packaging (Akromah et al., n.d.).

7.4. Textiles

MBCs in textiles have gained attention for their sustainable and eco-friendly characteristics. The mycelium proves instrumental in crafting a robust and adaptable material capable of replacing traditional textiles across various applications. The progress in MBCs leather and textiles has resulted in the emergence of innovative clothing and apparel collections integrating mycelium technology (Aiduang et al., 2022). Examples include MycoTex (MyCoTex*, n.d.*), Mycotech Lab (Mycotech*, n. d.*), Fine Mycelium (Materials—Fine Mycelium*, n.d.*), and Air Mycelium (AirMycelium*, n.d.*). The scope of production has extended beyond the creation of leather and textiles. Such as biodegradable fabrics where MBCs can be used to create biodegradable fabrics as an alternative to synthetic materials. These fabrics can decompose naturally, reducing the environmental impact associated with conventional textiles. Its application even extends to footwear products whereby MBCs can be utilized in the production of shoe components, such as insoles and uppers. These materials offer durability, flexibility, and breathability, making them suitable for sustainable and comfortable footwear.

Further research is still continuing to seamlessly integrate mycelium into textile with various fungal species and substrates. Silverman et al. (Silverman et al., 2020) developed mushroom mycelium composites for footwear products, which aims to reduce solid waste, resource depletion, and material toxicity in the footwear industry. The authors described the materials and methods that tested two mushroom species, namely king oyster (*Pleurotus eryngii*) and yellow oyster (*Pleurotus citrinopileatus*), and two fabric levels on the density and compressive strength of the composites. The sustainability characteristics of the MBC and their potential applications as biodegradable shoe soles is promising. The components, such as chicken feathers, natural fiber mat, husk psyllium, and mushroom spawn, are sourced from natural and renewable sources. The mycelium composites, derived from edible mushrooms, are biodegradable, with all ingredients being nonhazardous for safe manufacturing, use, and degradation. After use, the MBCs shoe soles can be composted, returning nutrients to the earth for agriculture, including mushroom cultivation, establishing a closed-loop cycle in biological metabolism.

8. Environmental and economic impacts of MBCs

It has been reported that 37 % of global greenhouse gas (GHG) emissions come from the manufacturing of building materials and the construction sector, including residential and non-residential as shown in Fig. 5 (United Nations Environment Programme, 2022).

Exploring new bio-based building materials is a potential solution. Over the past decade, bio-fabrication has gained importance in architecture, becoming integral to sustainable building strategies. MBCs, produced through a low-energy and carbon-neutral process, align with circular economy principles and sustainable building concepts (Jones et al., 2020a; Vašatko et al., 2022). These composites have diverse applications in terms of scale, functionality, and use, with architects,

Table 3
Mycelium production via SSF.

Fungal species	Inoculum	Solid-State Fermentation	Result	Ref.
Pleurotus ostreatus, Flammulina velutipes, Hericium erinaceus	Fungi culture maintained on potato dextrose agar (PDA) medium incubated in the dark for 7 days at 26 °C until good mycelium growth. This block was then inoculated in liquid solution containing; 10 g of peptone, 20 g of glucose, 3 g of KH_2PO_4, 10 mg of vitamin B1, 1.5 g of $MgSO_47H_2O$, and 1 L of distilled water. Incubation time = 7 days at 26 °C. Agitation rate = 160 rpm	Substrate – 5 g of distilled water +5 g of soybean meal powder +3 mL of incubated fungi culture. This was incubated for 14 days in the dark at 28 °C. Then the substrate was removed and dried at 60 °C for 24 h.	Successful production of mycelial biomass.	Wang et al. (2023)
Tuber magnatum	Fungi culture maintained on PDA medium at 25 °C until good mycelium growth. A 1 cm^2 block was then inoculated in pre-sterilized PDA medium. Incubation time = 3 days at 25 °C. Agitation rate = 120 rpm	Substrate – 500 g of (distilled water + soybean + red adlay) was inoculated with 10 mL of incubated fungi culture. This was incubated for 21 days in the dark at 25 °C. Then the substrate was removed and dried at 45 °C to reduce the moisture content to 10 %.	For *Tuber magnatum* fermentation, a 3:1 ratio of red adlay and soybean is recommended as a medium.	Hsu et al. (2022)
Mucor circinelloides	Fungi culture maintained on PDA plate incubated for 4 days at 28 °C until good mycelium growth. This block was then inoculated in liquid solution containing; glucose, $MgSO_47H_2O$, diammonium tartrate, KH_2PO_4, Na_2HPO_4, yeast extract, $CaC_{12}\cdot 2H_2O$, $FeC_{13}6H_2O$, $ZnSO_47H_2O$, $CuSO_45H_2O$, Co $(NO_3)_26H_2O$, $MnSO_45H_2O$, agar, distilled water. Incubation time = 4 days at 28 °C.	Substrate – a cellophane placed initially on the PDA plate was removed and the mycelial biomass was extracted and dried.	Successful production of mycelial biomass.	Xin et al. (2022)
Phanerochaete chrysosporium	Fungi culture maintained on PDA medium at 37 °C for several days until good mycelium growth. A spore suspension was first prepared by scraping the spores and mixing in distilled water. This spore suspension was then inoculated in liquid solution containing; Sterile potato dextrose, Pb $(NO_3)_2$. PH = 6.8. Incubation time = 21 days at 37 °C. Agitation rate = 150 rpm	Substrate – 35 g of 2 mm straw + Pb $(NO_3)_2$ solutions was inoculated with 2.1 mL of incubated fungi culture. This was incubated for 45 days in the dark at 37 °C. Then the substrate was removed and dried.	This study showed that the employed bio-treatment technology can be successfully used in mycelial biomass production using SSF.	Huang et al. (2010)
Mortierella isabellina	Fungi culture maintained on PDA plate incubated for 8 days at 28 °C. A 0.2 cm disk was cut from the cultured PDA and then inoculated in new PDA dishes. Incubation time = until the fungal colony occupied the 3/4 of the dish. Temp. = 28 °C.	Substrate – 25 g of pear pomace + KNH solution was inoculated with 1 mL of incubated fungi culture. This was incubated for 10 days at 28 °C under constant aeration. Then the substrate was removed and dried.	The use of pear pomace is suitable as it does not add to the overall fermentation costs.	Fakas et al. (2009)
Ganoderma lucidum	Fungi culture maintained on yeast medium plate (made from 10 g/L maltose, 20 g/ L glucose, 4.6	Substrate – 35.2 g elm wood chips + (0.4 g lime, 0.4 g sucrose and 60 mL wheat bran	Successful production of mycelial biomass and the water content was important	Hu et al. (2022)

(continued on next page)

Table 3 (*continued*)

Fungal species	Inoculum	Solid-State Fermentation	Result	Ref.
	g/L KH_2PO_4, 2 g/L tryptone, 2 g/L yeast extract and 0.5 g/L $MgSO_47H_2O$) was incubated at 28 °C until mycelium growth.	juice) was inoculated with 0.9 cm disk of incubated fungi culture. This was incubated for 21 days at 28 °C. Then the substrate was removed and dried.	during the fermentation process.	
Auricularia auricula	Fungi culture maintained on PDA plate. Other parameters are not specified.	Substrate – corn straw, soybean meal, bran, $CaSO_4$, CaO at mass ratio of 72:8:18:1:1 + (bean sprout juice and deionized water) was inoculated with 1 cm^2 of incubated fungi culture. This was incubated for 10 days at 26 °C. Then the substrate was removed and dried.	This study proved the cultivation process of wood-rotting edible fungus (*Auricularia auricular*) with corn stalk as substrate for enhanced mycelium growth.	Lu et al. (2022)
Phellinus linteus	Fungi culture maintained on PDA plate incubated for 14 days at 25 °C. Later same was stored at 4 °C up to 3 months. A 1 cm × 1 cm block was then inoculated in spawn medium containing; Glucose and potato dextrose broth. Incubation time = 7 days at 25 °C. Agitation rate = 120 rpm	Substrate – 60 g of brown rice +75 mL of water was inoculated with 6 mL of liquid spawn. This was incubated at 25 °C for 8 weeks. Carbon sources added to fermentation medium - fructose, glucose, mannose, sucrose or lactose. Nitrogen sources - malt extract, yeast extract, glutamic acid or peptone. Then the substrate was removed and dried.	The optimum mycelial biomass growth occurred at malt extract addition, sucrose addition, 55 % water content of grain medium, and an initial pH of 5.5.	Liang et al. (2020)

Table 4
Property enhancement through heat treatments and post-processing.

Fungal species & substrate	Treatments/post-processing	Results	Reference
Pycnoporus sanguineus Coconut powder substrate with Wheat bran supplement.	Drying heat treatments at i) at 50 °C, 60 °C & 70 °C for 24 h ii) at 50 °C, 60 °C & 70 °C for 48 h iii) at 50 °C, 60 °C & 70 °C for 72 h	Mechanical properties: Compressive strength – longer heat treatment time reduced the compressive strength. The compressive strength obtained ranged from 134 to 200 kPa. Toughness – the bio-composites that performed poorly during the compression test also had poor toughness. The high heat treatment reduced the mycelium network flexibility, reducing the ability to absorb the mechanical stress. It was found that certain mechanical properties could be achieved by varying the heat treatment time at constant temperature. Heat treatments above 60 °C & 48 h affected the mycelial growth and was ineffective treatment for the composites.	Santos et al. (2021)
Pleurotus ostreatus, Trametes multicolor. Substrates - straw, cotton and sawdust	Heat pressing at 150 °C and cold pressing at 20 °C. Applied force = 30 kN for 20 mins.	Heat pressing improved the stiffness, strength and homogeneity of MBCs. Further, the heat-pressed MBCs produced similar elastic modulus and density as wood and cork. Heat and cold pressing was the main reason for high tensile strength and not the chosen species of fungi and substrates. The flexural strength decreased from heat-pressed to cold-pressed to unpressed composites. Water absorption properties were not dependent on the pressing condition, type of fungal species or substrate.	Appels et al. (2019)
Ganoderma lucidum Substrate - sawdust and	First – heat treatment at 70 °C for 48 h and allowed to cool to room temperature, Next – heat-pressed	Flexural strength – decreased under tropical weathering conditions. Tensile strength – was higher for coated	Chan et al. (2021).

(continued on next page)

Table 4 (*continued*)

Fungal species & substrate	Treatments/post-processing	Results	Reference
empty fruit bunch.	at 120 °C, 20 MPa, for 50 mins, Finally, heat treated at 50 °C for 24 h.	samples compared to uncoated samples, decreased under tropical weathering conditions.	
	Osmo oil-based coating was applied to half of the samples and subjected to mechanical tests at varying weathering conditions.	Compressive strength – decreased under tropical weathering conditions.	
Ganoderma lucidum Substrate - cotton stalk	Water immersion followed by heat pressing at 200 °C for 6 mins. Heat pressing the MBCs with 20, 30, 40 and 50 % water uptake.	Water immersion greatly enhanced the mechanical properties, 30 % water uptake produced the highest mechanical properties. Greater than 30 % water uptake had nil effect on the mechanical properties due to excessive water stuck in the cell lumen.	Liu, Li, Long, Sheng, Xu, Wang (2020).
Different stain by Ecovative Design Substrate - hemp pith and cotton mat. Skin fabric – natural burlap	Sandwich structure and heat-pressed at 110 °C for 24 h.	The woven mat at the surface improved the compressive strength, however, had nil effect on the tensile strength.	Ziegler et al. (2016)

designers, and enthusiasts incorporating them into designs. However, while MBCs are environmentally friendly in many aspects, they are not entirely carbon neutral. The production process involves several stages where carbon emissions can occur. Cultivating mycelium typically requires a substrate like agricultural waste, which often needs to be pretreated through processes like pasteurization or sterilization, consuming energy (Alaux et al., 2024). Additionally, maintaining optimal growing conditions for mycelium involves energy-intensive climate control such as humidity, temperature, and sometimes light. Transportation of raw materials and final products also contributes to the carbon footprint. Although mycelium composites are biodegradable and can sequester carbon during growth, these factors make the overall process not completely carbon-neutral (Carcassi et al., 2022; Volk et al., 2024). The carbon footprint can be greatly decreased by developing, producing, and transporting goods using renewable energy sources. Moreover, energy consumption can be reduced by increasing the effectiveness of the production, sterilization, and growing processes.

Diverging from traditional insulation materials like mineral wool, EPS, and polyurethane foam, mycelium insulation sets itself apart with complete biodegradability. In contrast to materials from non-renewable sources resistant to biodegradation, mycelium's integration has potential environmental benefits by mitigating impacts linked to waste generation, fostering nutrient cycling, and enhancing soil vitality. Research indicates that mycelium, serving as a binding agent, initially decomposes, with a notable 43 % mass reduction observed in inert samples after sixteen weeks (Wylick et al., 2022). Disintegration rates hinge on factors such as material composition, manufacturing technique, and degradation complexities involving equipment, materials, and environmental conditions. Unlike conventional insulation persisting in ecosystems, mycelium insulation provides a circular and environmentally responsible alternative, offering profound biodegradability. Moreover, it becomes a significant avenue for carbon sequestration, absorbing and storing atmospheric carbon in its biomass to mitigate GHG emissions (Al-Qahtani et al., 2023). In a study by Luksta et al. (Luksta et al., 2021) showed that the mycelium insulation material has the lowest emissions per cubic meter, resulting in the overall lowest cumulative GHG emission value during the production process. Mycelium insulation material, in total, emits 3.58 $MtCO_2eq$. When factoring in CO_2 absorption, the estimated absorption for mycelium insulation is 6.26 $MtCO_2eq$. In comparison, synthetic materials have higher emissions: EPS at 4.3 $MtCO_2eq$, extruded polystyrene insulation (XPS) at 4.98 $MtCO_2eq$, polyurethane at 8.48 $MtCO_2eq$, and phenolic foam at 12.7 $MtCO_2eq$.

As the MBCs reach the conclusion of their life cycle, these composite materials demonstrate biodegradability and can serve as a foundation for cultivating new iterations of materials. Consequently, MBCs support the upcycling of organic waste, facilitate low-energy material manufacturing, and offer a biodegradable alternative to existing architectural materials (Houette et al., 2022). The key obstacle is the limited cost competitiveness of mycelium materials compared to conventional plastics. The challenge arises from the lack of a clear pathway for scaling

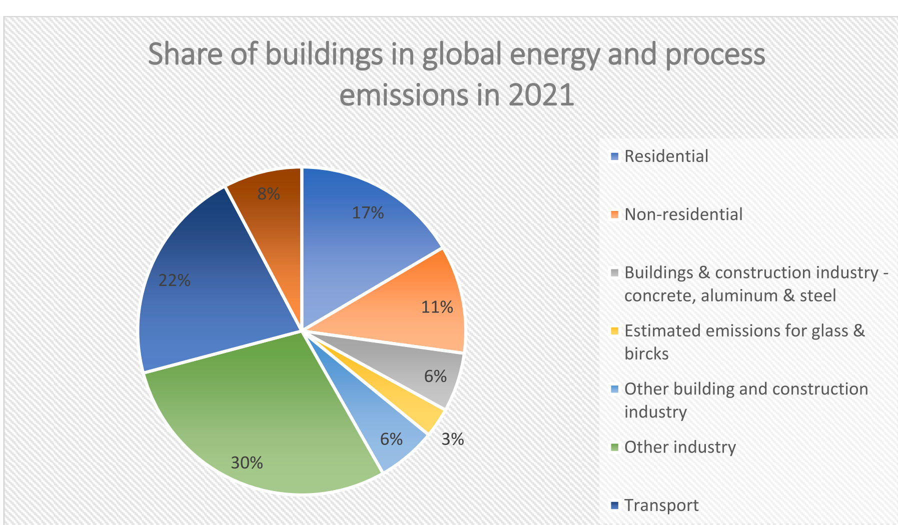

Fig. 5. Share of buildings in global energy and process emissions in 2021.

up mycelium material production, requiring the establishment of a new industrial infrastructure. Uncertainties in scalability result from significant capital investments, particularly for the extensive space and controlled environment needed in large-scale fermentation setups. Companies like Ecovative, MycoWorks, and Mogu, investing in mycelium materials, specialize in the field, while existing industrial biotechnology companies remain cautious and hesitant about this innovative approach.

Determining the economic feasibility of using MBCs materials for building is challenging due to limited research. A study by Osman (2023) suggests that the cost-effectiveness of MBCs materials depends on their cost competitiveness compared to other building materials. The study assumes that if constructing with MBCs is cheaper, the cost savings are invested at the current interest rate. The Consumer Price Index (CPI) is then used to adjust the building costs over time. MBCs materials are deemed economically competitive if, by the end of their expected lifespan, the investment of the initial cost savings, adjusted by the CPI, surpasses the maintenance costs of a building. Their study employed various interest rates to assess how the investment of the cost savings impacts the economic feasibility of MBC materials over time compared to other building materials. The amount of these savings varies depending on the particular application, production volume, and geographic considerations. When comparing the cost of manufacturing MBCs to traditional materials, the cost fluctuates depending on several aspects like labour costs, production procedures, raw material availability, and market conditions (Aiduang et al., 2024). MBCs have the potential to be more cost-effective because they use waste materials from industry or agriculture, use energy-efficient production techniques, and have a smaller environmental impact. However, it can be difficult to provide a precise cost comparison and calculate the percentage of cost savings when compared to traditional materials.

9. Challenges and future directions

9.1. Manufacturability

Despite the benefits of MBCs in mechanics, lightweight attributes, and eco-friendliness, they encounter challenges for large-scale applications. Unlike conventional materials like steel and polymer, mycelium biomaterial lacks production standardization. Customizing substrates for specific fungi to optimize yield and mechanics remains unclear. Testing each of over a million fungal species individually is impractical. Instead, understanding the structure-mechanics relationship across different fungi classes is crucial. MBCs cannot be rapidly mass-produced like polymer foams; growth takes about two weeks or more. Automated control of growing factors without human labour is essential. The contribution of each building block to the interface with wood fibers and its impact on the fibrous network's integrity is unclear (Yang et al., 2021). Addressing these issues is vital before introducing the material to architects and exploring broader industrial applications.

Another challenge involves the durability of MBCs and the delicate balance between biodegradability and product performance. The incomplete development of the production process on a larger scale result in limited information on life cycle assessments. Additionally, there's a scarcity of studies examining the material's long-term performance, crucial for applications in the construction sector. Achieving material reproducibility in mass production is challenging due to the inherent biological nature of mycelium materials, which is highly variable and responsive to environmental conditions. Biological stochasticity, even under identical conditions, can lead to variations in the material's composition and behavior during growth, making it difficult to guarantee consistent properties (Peeters et al., 2023).

9.2. Consumer acceptance

Consumer acceptance is another concern, as the inherent variability and 'imperfections' in organically grown products may not always align with consumer preferences. Embracing these characteristics as integral components of a living organism could be a potential solution. Bonenberg et al. (Bonenberg et al., 2023), investigated the acceptance of MBCs for interior design applications by conducting consumer tests to measure the sensory, hedonic, and ecological aspects of MBCs and compared them with chamotte clay, a ceramic material. The results showed that MBCs were generally perceived as neutral or pleasant, original and eco-friendly, but less visually appealing and less suitable for modern interiors than chamotte clay. Addressing the aesthetic and perceptual challenges, can lead MBCs for potential commercialization in the future. Therefore, creating awareness and education about the benefits and properties of MBCs, as well as making them more widely available and affordable, could help increase their popularity and adoption among consumers.

Given the emerging nature of research on MBCs, numerous questions remain to be addressed before their integration into permanent architectural projects. Specifically, further studies are needed to investigate the influence of particle shapes, composition, and distributions, as they have a substantial impact on mechanical properties. The optimal substrate particle size, striking a balance between mycelial growth and mechanical performance, is still under investigation. Additionally, research is ongoing on how higher substrate density can impede air transmission, potentially limiting mycelial growth within the substrate if aeration is not artificially introduced (Rigobello and Ayres, 2022).

9.3. MBCs potential in analytical chemistry

From a green chemistry perspective, the imperative is to create materials that are fully biodegradable. While MBCs are commonly explored for construction and packaging, their potential extends to specialized applications, notably in analytical chemistry. Analytical chemistry often relies on minimizing harmful solvents, especially in techniques like liquid chromatography. MBCs, with their hydrophobic nature, hold promise for applications like thin-layer chromatography. Ensuring material inertness is crucial. These composites may also serve as fibrous networks for innovative green filtration and adsorption systems, matching conventional materials' mechanical and thermal properties. However, challenges like material density and moisture absorption persist in widespread commercialization. Nonetheless, adjusting parameters such as mycelium strain, process conditions, growth substrate, manufacturing techniques, and post-treatment methods can optimize material properties and performance (Rafiee et al., 2021).

To overcome the constraints of MBCs, it is essential to conduct further studies prior to their integration into permanent buildings. This involves exploring novel substrate/fungus combinations, assessing the impact of diverse parameters (such as fungal species, substrate type and size, growth environment, and post-growth treatments) on material properties, predicting material behavior, ensuring uniform material properties, and characterizing the accumulation and decomposition of toxic chemicals.

9.4. Biomedical implementation

Chitin, a key element of mycelium, functions as a natural polymer abundant in fungal cell walls and crustacean exoskeletons. Its versatility extends to diverse biomedical applications. Both chitin and its derivative, chitosan, are extended linear macromolecules suitable for electrospinning fibers, which is a method that employs an electric field to draw charged polymer chains from solutions, forming a continuous fiber of aligned chains (Jones et al., 2020b). Chitin has been effectively applied in producing nonwoven cloths and gels for wound dressing, interacting with open tissue during healing. The multiscale structures of these materials at the interface with biological tissues warrant thorough investigation. While both crustacean and fungal chitin contribute to wound-dressing research, distinctions arise in their structures, properties, and processing methods. Essential extraction is required for both chitin types, as crustacean chitin tends to bind with sclerotized proteins and minerals, while fungal chitin binds to other polysaccharides like glucans. Highly purified crustacean-derived chitin and chitosan dominate various applications. Despite its simpler extraction process, fungal chitin has received less research attention, yet it boasts advantages in quantity and availability. Notably, the growth of mycelium, the source of fungal chitin, faces no seasonal or regional restrictions, unlike crustaceans (Yang et al., 2021). It is important to note that while research in this field is ongoing, there may still be challenges to address, such as optimizing material properties, to better align or suit with biomedical applications as mentioned.

9.5. MBC optimization and production

9.5.1. Improving production of chitin and glucan

The mycelium component in MBC has previously been criticized for its limited mechanical performance, often seen as a major drawback for the material's broader adoption in structural or high-stress applications. This perception stems from the fact that mycelium, while highly sustainable and lightweight, has traditionally been viewed as weaker compared to conventional materials like synthetic polymers or metals. However, recent research focusing on the chitin-glucan extracts which is an essential structural component of mycelium have shown that the mechanical properties of mycelium can be significantly improved. Chitin, a biopolymer found in the cell walls of fungi, is known for its stiffness and strength, while glucan contributes to the flexibility and durability of the mycelium network. This suggests that when properly extracted and processed, chitin-glucan extracts derived from mycelium can offer enhanced mechanical performance, making the mycelium binder itself a more robust and functional component in composite materials thus, further optimizing the mechanical performance of MBCs (Fazli Wan Nawawi et al., 2019). Potential research could focus on refining the extraction and processing of chitin-glucan from mycelium to develop stronger and more durable binders. By improving the material properties of the mycelium itself, the reliance on synthetic reinforcements or other additives could be reduced, making MBCs even more environmentally friendly and sustainable. Additionally, there is potential for developing hybrid composites that combine mycelium with other bio-based or recycled materials to further enhance strength and functionality without a trade-off in sustainability. Another avenue for future research could involve bioengineering mycelium strains to optimize their production of chitin and glucan, thereby improving the inherent mechanical properties of the material (Jones et al., 2018). This could lead to MBCs that are not only stronger but also more customizable to specific applications, whether in construction, packaging, or consumer goods. By addressing the mechanical limitations traditionally associated with mycelium, future developments could greatly expand the range of industries and applications in which MBCs can be effectively used.

9.5.2. Cold and hot pressing of MBCs

One of the most promising ways to improve the mechanical properties of MBCs is through physical processing techniques, such as cold and hot pressing. These techniques have shown great promise in enhancing the structural integrity of MBCs, by increasing density, reducing porosity, and improving the bonding between the mycelium fibers and the reinforcement materials. Cold pressing involves applying significant pressure to the mycelium composite at room temperature or slightly elevated temperatures. This technique compacts the material, eliminating air pockets and reducing porosity, which in turn enhances the overall density of the composite. The higher the density, the stronger the composite becomes in terms of both tensile and flexural strength. Additionally, cold pressing leads to a more uniform distribution of the mycelium and any reinforcement materials, contributing to the material's overall mechanical consistency. Importantly, cold pressing preserves the biological nature of the mycelium, ensuring that the material remains biodegradable. However, while cold pressing improves strength, it may not be sufficient for applications requiring the high mechanical performance, such as load-bearing construction materials.

In contrast, hot pressing applies both heat and pressure, providing an additional advantage by inducing thermal curing of the mycelium matrix. The heat softens the chitin-glucan network within the mycelium, which allows it to flow and fill any micro-voids in the composite, leading to stronger and more cohesive bonding. This results in significantly enhanced mechanical properties, such as greater tensile and flexural strength, making the material more suitable for a broader range of applications, including more demanding structural uses. Hot pressing also improves the material's resistance to deformation under compressive and tensile forces, making it more durable and suitable for various industries, from construction to furniture manufacturing. Furthermore, the dimensional stability of hot-pressed MBCs is often superior, reducing the risk of warping or shape distortion, which is essential for the production of durable and dimensionally stable products. The advances in cold and hot-pressing techniques are setting the stage for future developments in MBCs. One aspect is the potential for further optimizing the material composition by blending mycelium with other natural fibers, nanoparticles, or bio-based polymers. This could significantly improve mechanical performance, enabling MBCs to meet the specific strength and durability requirements of various applications. For example, optimizing the composition of MBCs could lead to stronger, lightweight composites for aerospace or automotive use, or more heat-resistant composites for electronic components. Additionally, as these processing techniques are refined, scalable manufacturing processes will become more feasible. This scalability is crucial for making MBCs a viable alternative to synthetic materials in mass-market applications. Industries such as construction, packaging, and automotive manufacturing are showing growing interest in sustainable materials, and with improved mechanical properties, MBCs could become a key player in these sectors.

9.5.3. MBCs optimization via design of experiments and computational modelling

The future development of MBCs will greatly benefit from a more scientific, data-driven approach that incorporates not only advanced optimization techniques but also structured experimental designs and computational modelling to fine-tune production parameters. MBCs are influenced by a wide range of factors, such as the type of fungi used, the choice of substrate, growth conditions, and processing techniques (including temperature, pressure, and moisture levels). These factors interact in complex ways, making it challenging to identify optimal combinations without systematic methods for experimentation and analysis.

One such approach is the Design of Experiments (DoE), which includes structured methodologies like the Taguchi method. The Taguchi method is particularly useful for optimizing manufacturing processes by systematically varying parameters to identify the most influential factors while minimizing variability. This approach helps to improve the robustness of MBCs production, ensuring consistent quality in mechanical properties across various conditions. By applying the Taguchi method, researchers can efficiently evaluate multiple variables with a limited number of experiments, making it a cost-effective way to optimize production processes. This method can help pinpoint the specific fungi-substrate interactions or processing conditions that lead to the best mechanical properties, such as strength and flexibility. Another powerful optimization tool is response surface methodology (RSM), which allows for the modelling and analysis of relationships between multiple input variables and the desired output properties of the composite. RSM is particularly well-suited for identifying the optimal combination of factors that yield the best mechanical performance of MBCs, such as the highest compressive strength or impact resistance. By using

RSM, researchers can create predictive models that can guide the fine-tuning of variables like temperature and pressure during processing, resulting in composites that meet specific mechanical performance requirements.

In addition, artificial neural networks (ANN) and other machine learning techniques provide a means for analysing large datasets to predict the behavior of MBCs under different conditions. These models can learn from previous experimental data and simulate the outcomes of various processing parameters, significantly reducing the need for costly and time-consuming physical experiments (Hamza et al., 2024; Lee et al., 2022). By using ANN, researchers can forecast the mechanical properties of MBCs based on a wide range of input variables, enabling the identification of hidden relationships and interactions between parameters that traditional statistical methods might miss. This could be particularly useful in optimizing the densification process during cold or hot pressing to enhance the material's strength. Moreover, genetic algorithms and multi-objective optimization techniques can also be applied to optimize multiple performance goals simultaneously, such as maximizing strength while minimizing weight or environmental impact – such as degradability study based on time. These methods can assist in fine-tuning the balance between mechanical performance and sustainability, a key factor in the commercial viability of MBCs.

The integration of data analytics and optimization methods will also enable an in-depth exploration of the interactions between various types of fungi and substrates. MBCs are highly adaptable due to the biological variability of fungi, and different species may interact with substrates in unique ways, leading to different material properties. By applying these advanced methods, researchers can systematically explore the potential of different fungi and substrate combinations, discovering those that offer superior mechanical properties or additional benefits such as fire resistance, water repellence, or biodegradability. Incorporating these advanced computational and experimental techniques into MBCs research is crucial for understanding the true capabilities of this material. By using optimization methods like the Taguchi approach, RSM, and machine learning, researchers can accelerate the development of MBCs by reducing reliance on traditional trial-and-error experimentation. This will allow for more precise control over production parameters, leading to composites that meet the demands of various industries, from construction to packaging and beyond. Furthermore, optimizing these materials for high performance will make MBCs more competitive with conventional materials, broadening their applicability in high-strength, high-performance settings.

10. Conclusion and future perspectives on MBCs

In conclusion, this literature review has offered a thorough exploration of the current and prospective role of MBCs in addressing environmental and economic challenges. Throughout the review, various critical points have emerged, shedding light on both achievements and areas warranting further investigation within this rapidly developing field.

One prominent observation is the evident synergy between commercial and academic entities, as evidenced by the ongoing release of innovative developments on digital platforms. Nevertheless, it is essential to acknowledge that related academic publications frequently lack essential data, potentially due to commercial sensitivities, thus revealing a gap in research transparency and dissemination.

Moreover, the question of the economic viability of scaling up MBCs production remains unresolved due to a paucity of literature addressing this aspect. Similarly, studies scrutinizing the long-term performance of MBCs, notably in construction applications, are scarce, indicating a pressing need for deeper exploration in this domain.

Consumer acceptance presents another obstacle, as the intrinsic variability and perceived "imperfections" of organically cultivated products may not consistently align with consumer preferences. Nonetheless, addressing aesthetic and perceptual challenges through heightened awareness, education, and enhancements in product accessibility and affordability could facilitate the eventual commercialization of MBCs.

Despite the promising attributes of MBCs, challenges persist, including the refinement of material properties for targeted applications, such as biomedical uses. Furthermore, the absence of standardized guidelines for selecting suitable fungal species and production process parameters underscores the necessity for uniform protocols and continued research in this area.

Looking ahead, several emerging trends and future perspectives offer promising directions for the further development of MBCs. Advances in biotechnology and materials science are expected to drive significant improvements in the scalability, efficiency, and versatility of MBCs. Particularly, the ongoing exploration of innovative fungal species and the refinement of cultivation techniques hold the potential to enhance material properties, making MBCs more competitive with conventional materials.

Furthermore, as the demand for sustainable and bio-based alternatives grows, there is a growing emphasis on the development of circular economy models for MBCs, focusing on reuse, recycling, and closed-loop systems. Consumer education and shifting societal preferences towards environmentally friendly products will also play a crucial role in the wider adoption of MBCs.

In light of these insights, it is clear that while substantial progress has been made in advancing MBCs technology, critical gaps and challenges remain. The future of MBCs will depend on sustained collaboration, interdisciplinary research, and innovative approaches to overcoming existing limitations. With continued effort, MBCs hold the potential to revolutionize material science and contribute to a greener, more sustainable future.

Ethics declaration

Review and/or approval by an ethics committee as well as informed consent was not required for this study because this literature review only used existing data from published studies and did not involve any direct experimentation/studies on living beings.

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Declaration of competing interest

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

Data availability

No data was used for the research described in the article. No data associated in this article has been deposited into a publicly available repository.

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