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Review

Mycelium based composites: A review of their bio-fabrication procedures, material properties and potential for green building and construction applications

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ABSTRACT

The quest for green products and technologies for applications in the built environment has led to the birth of a new generation of sustainable materials, among which are mycelium-based composites. They are biocomposites derived from the growth of filamentous parts of fungus on an organic substrate. Their low carbon footprint, low energy and processing cost, biodegradability, and attractive range of properties, have made them highly demanded as alternative materials for use in the building and construction sector. Their bio-fabrication procedures, material properties, and prospects in building and construction applications have hardly been considered in a single review. It was noted that these composites have several potential benefits from economic, technical, environmental, and green credentials perspectives which make them desirable for building and construction purposes. However, their low mechanical properties, high water absorption, and lack of standardized development methods limit their applications to semi-structural and non-structural materials such as paneling, furniture, and decking. Future research should aim at reconciling its varying mechanical properties based on substrate, fungus species, growth condition, and processing method. Also, efforts should target improving its weathering and hydrophilic propensities, and scalability, factors that could undermine its long-term commercial success and applicability.

1. Introduction

Over the last two decades, there has been a widespread global campaign towards the development and utilization of more sustainable materials and technologies for the development of industrial and technological products [1]. In the building and construction sector, this crusade has even been more intense – considering the contribution of this sector to environmental issues [2]. Globally, the building and construction industries are responsible for a larger percentage of carbon emissions and the generation of non-biodegradable waste, which in turn have adverse effects on the ecosystem [3,4]. Products such as cement, concrete, metals, and polymers which are conventionally used in this sector, often require high energy consumption during production, high material and processing costs, complex equipment, and production infrastructure for design and product development, recycling difficulties, and create environmental pollution problems [5,6]. Poor biodegradability is also a crucial setback for most of these synthetic building and construction materials, as reports state that as many as a

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hundred years could be required for them to decompose completely [7]. This lack of adequate biodegradability is a huge drawback to the potential contribution of this sector to the circular economy, which is projected to offer as much as $4.5 trillion to the global economy as benefits by the year 2030 [8]. Furthermore, the increase in industrialization and technological advancement has resulted in increased energy demand and consumption. This has resulted in more pressure on non-renewable energy resources, leading to a dramatic reduction in reserves [9].

The threats and concerns posed by the exploration, processing, production, and utilization of synthetic materials from non-renewable sources (petroleum and natural gas) have given latitude to the consideration of renewable biodegradable materials for several technological applications, including the building and construction industries [10]. Currently, biocomposites known as mycelium-based composites are among biomaterials under consideration as building and construction materials [2,11].

Mycellium-based composites derive their name from mycelium, the filamentous (mushroom-forming) part of a fungus. When these fibers are allowed to grow on an organic substrate such as by-products and waste streams from forestry and agriculture, it results in the development of fascinating biocomposite with a wide range of properties and applications [7,12]. Organic materials such as straw, sawdust, woodchips, cotton, and rice husk, among others, have been used as organic substrates for the development of mycelium-based composites [13,14]. As the fungi colonize the substrate, the hyphae of the fungus create an entwined three-dimensional filamentous linkage through the cellulose, hemicellulose, and lignin-rich substrate by absorbing its nutrients and bonding with the substrate to form mycelium-based materials (MBMs) [15]. The thick fungi skin (mycelium) which is formed after full colonization of the substrate, is subjected to heat to remove the moisture content and kill the organism (above a critical temperature). The product formed is an inert, lightweight, and biodegradable material known as mycelium-based composite (MBC) [10]. These mycelium-based composites (MBCs) are clean, safe, strong, and biodegradable with huge potential to substitute fossil-based and synthetic materials such as polyurethane and polystyrene [6,15]. They are also hyped as having better recycling efficiency which should contribute to a circular economy alongside environmental benefits such as lower emissions and better land use [16].

Currently, MBCs are been considered for product development in packaging [17], industrial artifacts [18], accessory materials [19], furniture [20], paper [12], building materials, textile films [21], insulation materials [2,22], acoustic and floor tiles [10]. In the building and construction sector, MBCs are enthused to create low-cost and greener building and construction materials, which could help reduce reliance on fossil fuel-based and other non-renewable- products [23]. Considering that building and construction is a sensitive sector where variability in product quality can result in sudden and unexpected failure, new products would require thorough structural integrity assessments for selection and commercial utilization. Several authors have already noted that the properties of MBCs are sensitive to several variables including the type of substrate, fungus type, growth conditions, and processing methods [6,13,24–25]. An in-depth knowledge of the relative effect of each of these variables can considerably lead to the optimization of the production process, leading to the development of products with the appropriate spectrum of properties suitable for the building and construction industries. Several reviews are already available on the development and use of MBCs [10,13].

Javadian et al. [2] reviewed the recent development and properties of MBCs that have been used in building and construction, especially as insulation materials, door panels, and window frames. The properties and use of MBCs in furniture as building panels and masonry blocks have been reported by Ghazvinian et al. [9]. The applications of MBCs manufactured from fungal biorefineries in construction materials were reviewed by Jones et al. [12]. It was reported that low thermal conductivity, high acoustic absorption, and fire safety properties were among the key properties that propelled MBCs for utilization in building and construction, particularly as insulation, paneling, and furnishings materials. Manan et al. [25] reviewed the effects of processing techniques on the properties and applications of MBCs. It was noted that MBCs have been identified as sustainable alternatives to conventional construction materials because of their comparatively low cost, fire-resistant or safety property, and environmentally friendly characteristics. However, Sydor et al. [26] acknowledged that the practical applicability of MBCs is limited by their poor strength and unreliability due to their high water absorption. These drawbacks are surmountable by the appropriate selection of mycelium base materials (fungal strain and substrate type) and by controlling the growth conditions [10]. Overcoming the identified problems of MBCs is expected to be the focus of research at present [7]. The current progress in the development of mycelium-based foams, sandwiches, paneling, decking, flooring, and furniture materials for construction structures has been evaluated by Yang et al. [5]. However, none of these reviews have attempted to review the bio-fabrication procedure involved in the manufacture of MBCs as well as a critical look at their material properties (physical, chemical, and mechanical) which are critical for their consideration for green building and construction applications. Therefore, this review effort was undertaken in light of the identified gap in the literature on the state-of-the-art studies on the production, properties, applications, and prospects of MBCs.

2. Method for selecting publications considered in this review

2.1. Basis for selection of published literature

An analysis of the published literature was performed to identify articles relevant to the title: Mycelium-based composites: A Review of their bio-fabrication procedures, material properties, and considerations for green building and construction applications. The Scopus database was utilised following an initial search of different databases. It has a greater number of papers that have been published on the subject, and also because of its widespread use, visibility of articles, and high level of reliability. The following terms were used to search the Scopus database for all the conference papers, monographs, and journal articles that were relevant to the study: "mycelium*" AND "mechanical properties*" OR "mycelium composite*" AND "carbon footprint*" OR "mycelium biocomposite*" AND "sustainable materials*" OR "mushroom biocomposite*" AND "bio-based building materials*" OR "fungal biocomposite*" AND "carbon footprint*" OR "fungal biocomposite*" AND "mechanical properties*". The use of these keywords in the search for title, abstract, and keyword field yielded 381 publications, however, only 128 of those papers were selected based on their relevance to the objectives of this study and year of publication.

2.2. Trend of scientific publication on mycelium-based composites from 1966 to 2023

The annual scientific contributions to the mycelium-based composites are given in Fig. 1. According to the Scopus database, the first publication on mycelium-based composites was published in 1966, and only one paper was published in that year. In 1966, 1974, 1975, 1982, 1983, 1987, and 1990, only one article was published in each of those years, while no article was published in the years in between. A slow, progressive increase in the number of published articles was observed in 1997, 1999, 2002, 2008, 2012, 2014, 2016, and 2017, while a decline was observed in the years in between. The publications steadily grew from 13 to 72 from 2018 to 2022.

The publication analysis is broken down by country and presented in Fig. 2, with 15 countries having greatly contributed to the research on mycelium-based composites. Only countries with at least 10 publications in the Scopus database were considered in this analysis. Due to the

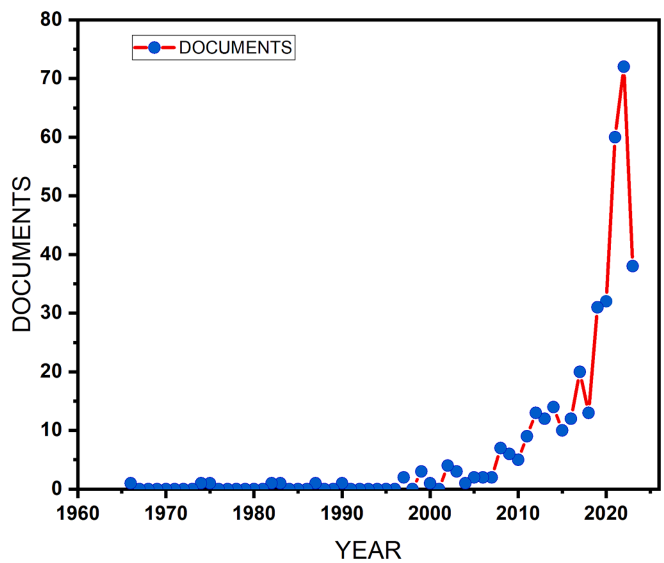

Fig. 1. Trend of scientific publication on mycelium-based composites from 1966 to 2023.

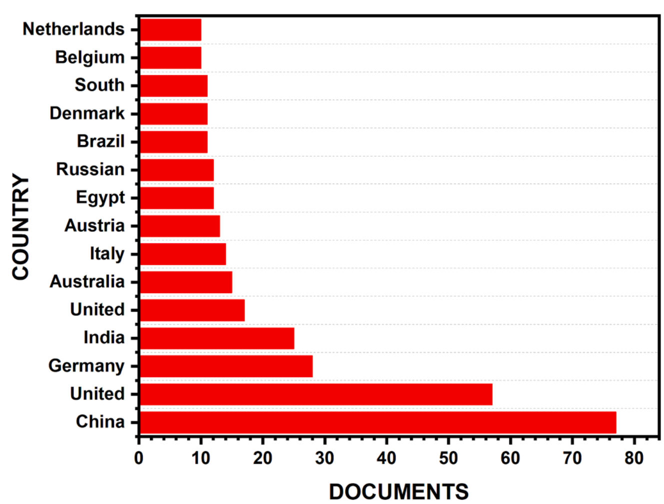

Fig. 2. Document by country or territory with at least 10 published articles in Scopus.

authors' international collaboration, several countries overlapped on the same paper. According to Fig. 2, China has the largest number of publications (74). Next on the list is the United States, with 57 articles; Germany, with 28 articles; India, with 25 articles; the United Kingdom, with 17 articles; Australia, with 15 articles; Italy, with 14 articles; Austria, with 13 articles; Egypt and the Russian Federation, with 12 articles each; Brazil, Denmark, and South Korea, with 11 articles each; and finally, Belgium and the Netherlands, with 10 articles each.

3. Production of Mycelium-based composites

3.1. Introduction

Fungi are eukaryotic organisms that exhibit diverse morphology and lifestyle with the ability to colonize large areas [27]. Mycelium Fungi colonize their substrate by digesting the nutrients in the substrates thereby growing within and outside the substrate to form a compact or fluffy layer known as fungal skin [25]. Generally, MBCs are manufactured through this bio-fabrication process involving the incubation or colonization of substrates with fungal mycelium followed by a drying/heating process to kill the organism and form a compact material [18,25]. The process of manufacturing MBCs is reported which can lead to a promising and inventive way to produce building materials from using the agro-waste materials [28].

In the study conducted by Appels et al. [13], MBCs were produced by hot-pressing the fungi skin at 150 °C for 20 min with a force of less than 30kN. The fungi skin was formed by growing exotic mushrooms on three different substrates including beech sawdust, rapeseed straw, and non-woven low-quality cotton fibre. The shape of the MBCs products depends on the shape of the substrate which acts as the mould [7]. In a related study, Attias et al. [18] produced MBCs by growing three samples of fungi species (*Colorius* sp., *Trametes* sp., *Ganoderma* sp.*)* on woodchips prepared by mixing ground residues of apple and vine crops with 1% flour, 3% wheat straw, and 62% distilled water. This was followed by the addition of 3% inoculum into the autoclaved substrate under sterile conditions. The samples were incubated at 23 °C and 95% humidity for 14 days before the samples were oven-dried for 48 h at 60 °C to produce the MBCs. Elsacke et al. [15] produced MBCs by the activities of various kinds of lignocellulosic substrates (flax, flax dust, flax long treated fibres, flax long untreated fibres, flax waste, wheat straw dust, wheat straw, hemp fibres, and pine softwood shavings) with mycelium spawn *Trametes versicolor* (M9912-5LSR-2 O447A). The substrates were processed by soaking the fibres in water for 24 h, blending them with fresh water to a particle size of 5 mm, and drying at 30 °C for 24 h before they were autoclaved for 20 min. at 121 °C and then allowed to cool down for 24 h. The MBCs were fabricated by mixing 20%wt. (weight percentage) of fibres, 70%wt. of sterile demineralised water and 10%wt. of mycelium spawn in polyvinyl chloride (PVC) mould. After 16 days of incubation, fully colonized substrates were dried in a convection oven at a temperature of 70 °C for 5 to 10 h. In recent studies, several researchers including Haneef et al. [6], Zimele et al. [14], Yang et al. [17], Attias et al. [18], Gezer et al. [19], Shakir et al. [20], Islam et al. [24] and Jiang et al. [29], Ghazvinian et al. [33] have produced MBCs following steps stipulated in Yang et al. [5]. These steps entail materials selection (fungal strain and feedstock), substrate sterilization, inoculation, moulding, incubation, heat treatment processes, and surface finishes (such as coating). The flow sheet showing the steps involved in the processing of MBCs is presented in Fig. 3.

3.2. Mycelium production steps

Generally, the production of MBCs involves the following protocols summarized into eight steps:

3.2.1. Selection of organism (fungal species)

The factors which inform the selection of appropriate fungi include growth rate, characteristic MBM density, homogeneity of mycelium skin, and the ease with which the fungi can be incubated [30]. The genetic traits of the organism (fungal species) have been identified as one of the factors that determine the properties of the MBCs [6,24]. It is imperative to select the most appropriate strain according to the substrate, growth conditions, or fermentation setup and proposed application [7]. Different results have been obtained in terms of material properties (Table 1) with the use of diverse fungi species during the production of MBCs [25]. It was reported that the activity of Trametes multicolor on rapeseed straw results in a smooth and foam-like structure whereas the colonization of P. ostreatus on the same substrate (rapeseed straw) produced MBMs with rough structure [13]. The characteristics of some fungi species concerning their activity with plant cells (wooden substrates) are discussed elsewhere [10]. However, the white rots saprotrophs species of fungi were noted to exhibit good substrate colonization rate, have strong mycorrhizal, endophytic, or pathogenic character, and are most efficient in digesting plant cell wall material (lignocellulose) due to secretion of ligninolytic enzymes. This is the reason why most filamentous species employed in the production of MBCs are white rot fungi strains [10,31]. In literature, only a few fungal

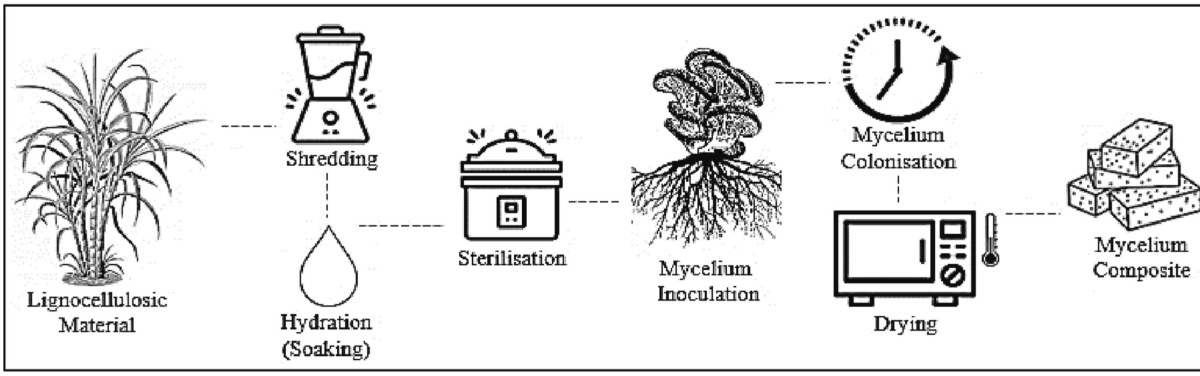

Fig. 3. Flow sheet showing the steps involved in the processing of MBCs (Lingam et al. [11], culled with permission from Elsevier).

species have been tested thus it may be rash to link any fungi strain with the production of MBCs with optimal material properties [10,32].

3.2.2. Selection of feedstock/organic substrates

The mushroom-forming organism (fungi) naturally grows on agricultural waste streams such as straw, fibres, sawdust, and/or woodchips among other organic and inorganic materials [2,12]. Many authors including Appels et al. [13], Manan et al. [25], and Ghazvinian et al. [33] stated that the kind of organic substrate affects the properties of the fungi skin produced after colonization of the substrate. The tensile strength [25], density [33], and water-holding capacity [13] of the fungal-based mycelium among other properties are highly sensitive to the type of substrate. Also, the addition of rice husk and glass particles to substrates has been shown to improve the fire-resistant properties of MBCs [34]. Therefore feedstock selection is critical in the production of MBCs, especially in situations where product quality is paramount. The envisaged large-scale production of mycelium necessitates the need to identify local sources for mycelium feedstock or substrate and to design the production capacity as a function of substrate availability [7]. Some agro-based materials for the bio-fabrication of MBCs as well as their petroleum-based counterparts are shown in Fig. 4. Table 1 compares the properties derived from various feedstock with diverse production parameters ranging from the type of fungi species to growth conditions and processing methods. To determine the feedstock with optimal MBC properties, it will be necessary to conduct studies in which the variables (such as fungus type, growth conditions, and processing methods) are kept constant with variable feedstocks.

3.2.3. Substrate sterilization method

The rivalry between the fungal strain of interest and unwanted microbes living on the substrate can limit the rate of colonization of the fungal species thereby reducing the product quality [32]. To improve the activity and colonization rate of fungi and prevent contamination of the fungi skin (mycelium) during the growth process, it is necessary to disinfect or sterilize the substrate or feedstock [10,35]. To achieve this purpose, the substrates are usually treated with chemical substances such as hydrogen peroxide or antimicrobial agents and/or by heat treating (autoclaving) the substrate at a preselected temperature and time [12]. Many authors including Haneef et al. [6], Elsacker et al. [15], and Appels et al. [36], have sterilized different kinds of feedstock by conducting heat treatment within the temperature range of 115 to 121 °C and durations within 15 to 28 min. Atila [35] also carried out substrate sterilization using hot water treatment under a pressure of 15lbs for 20 min. This was then followed with chemical treatments using 1% formaldehyde and bavistin solutions. The author established that cheaper and more easily applicable scalping in hot water (80 °C) and chemical treatment may be used for the sterilization of substrates instead of sterilization with an autoclave.

3.2.4. Inoculation process

Inoculation is the process of mixing (or interacting) the substrate with the fungal mycelium to stimulate the growth of the hyphae and facilitate the development of compact fungal skin (mycelium) [29]. There are two main techniques reported in the literature for inoculating the substrate with mycelium, namely, grain-based inoculation and liquid-based inoculation [22]. Some researchers including Holt et al. [22] and Ahmadi [38] have used the grain inoculation technique thereby pre-growing mycelium on grain spawn which in turn is used to inoculate the substrate in various mixing ratios. In the study carried out by Elsacker et al. [10], the liquid-based inoculation method was employed. It has been reported that the growth rate of mycelium is increased when inoculation is performed using glucose, starch, maltose, and lactose [20]. The effect of these inoculation methods on the properties (especially dimensional stability and compressive strength and Young's modulus) of MBCs is reported elsewhere [15,17,22].

3.2.5. Mould design/packing method

Studies conducted by Elsacker et al. [15], and Yang et al. [17] have established that the substrate mould design affects the mechanical properties (compressive strength, stiffness, or Young's modulus) of the MBCs after production. This manufacturing stage is important because the shape, density, and stiffness of MBCs produced depend on the mould condition where the inoculated mixture of mycelium and substrate are packed [10]. As the hyphae grow in the mould, the quantity of mycelium deposit increases and results in densely packed MBMs shaped by the mould [7,38]. It has been observed that the packing method also affects the dimension and fibre orientation of the fungi skin (mycelium) produced [23]. Several packing methods have been tried including packing in polyethylene bags [19], porous bags [18], PVC moulds [15], and plastic thermo-formed moulds [13]. Packing moulds are usually sealed filtered air-permeable covers to maintain a micro-climate condition [10]. Moulding of mycelium base materials still requires more research attention to determine the optimal mould design parameters necessary for the production of quality MBCs products.

3.2.6. Colonization of substrate/ incubation process

MBMs are produced when mycelium colonizes the substrate within the mould setting during the incubation process [13]. The production of thick fungal skin during incubation of mycelium usually takes place in two stages: the first stage where mycelium bonds with the mould and the second stage where the fungi skin grows outside the mould to form a compact MBM product [10]. Fungi are specific such that every fungal species thrives in definite environmental conditions [22]. However, optimal growth conditions for most fungal strains have been specified to occur at room temperature (21 to 30 °C), humidity, and pH levels within the ranges of 70 to 100% and 5 to 8 respectively [6,38]. Well-ventilated dark environments with low CO_2 concentrations have been reported to favour the growth of mycelium. Dense fungi skin is obtained when the

Table 1
Properties of some conventional materials with respect to the properties of MBCs.

Properties for building and construction materials	Cement	Polymers	Gypsum	MBCs
Density (kg/m^3)	1800–1950 [59]	22–30 [59]	417–945 [60]	110–330 [39]
Compressive strength (MPa)	i. Cement: 3.45 [17] ii. Clay brick: 8.6–17.2 [14]	Plastics: 0.069–0.40 [14] Phenolic formaldehyde resin: 0.2–0.55 [12] Polystyrene foams: 0.03–0.69 [12] Polyurethane: 0.002–48 [12]	0.06–0.55 [60]	0.36–0.52 [1] 0.17–1.1 [12]
Water absorption (wt.%)	Cement: 12 [17] Plywood: 5–49 [12]	Plastics 6.9 [28] Phenolic formaldehyde resin (1–15) Polyurethane: 0.01–72 Polystyrene: 0.03–9 [12]	52 [102]	200 [1,103]. 40–580 [12]
Flashover time (s)	Particleboard: 173 [12]	Polystyrene foam: 61 [12]	–	311–370 [12]
Properties for insulation materials/ Ref.	sheep wool	Polystyrene	Kenaf	MBCs
Thermal conductivity (W/m.k) [47]	0.05	0.03	0.04	0.05–0.07
Properties for acoustic damping materials/ Ref.	Ceiling tiles	Urethane foam board	Plywood	MBCs
Noise absorption capacity (dBa) [12]	61	64	65	52–54

Properties for miscellaneous applications

Properties	Polymers	Plywood	MBCs
Flexural strength (MPa)	Polyurethane: 0.21–57 Phenolic formaldehyde resin: 0.38–0. Polystyrene foams: 0.07–0.70 [12]	35–78 [12]	0.87–15 MPa [2]. 0.05–0.29 MPa [12]
Tensile properties (MPa)	Polyurethane: 0.08–103 Phenolic formaldehyde resin: 0.19–0.46 Polystyrene foams: 0.15–0.7 [12]	Tensile strength:10–44 Compressive strength: 8–25 [12]	0.03–0.24MPa [2] Up to 0.343MPa [104]
Elastic Modulus	Polystyrene: 3400MPa [105]	Particleboard from Macadamia Nutshell and Gum Arabic: 1810MPa [106]	97MPa [2].

rate of airflow is high [7]. The overriding advantage of incubating fungi in the darkness is that dark areas often generate the moisture that the spores require to replicate [38]. Also, mycelium has been shown to thrive in the presence of light under high C O_2 concentrations [36]. Mycelium incubation time has been observed to vary from 5 to 42 days depending on the volume of the inoculated substrate [6,17]. The effect of fungi incubation time on the mechanical behaviour of MBCs is discussed elsewhere [10,17].

3.2.7. *Drying process*

At maturity, the grown MBMs are subjected to heat treatment at a pre-selected temperature and time to kill the organism and eliminate the moisture content in the MBCs produced in the process [10]. Hot-pressing and oven drying are the most common methods employed for dehydration and densification of MBCs after incubation which often leads to improvement of their mechanical properties [12]. Several authors have employed diverse methods for drying including oven backing at a temperature range of 60 to 125 °C for 2 h [6,38]; convection heating using solar dryers at 82 °C for 12 h and thermal pressing at 250 °C for 20 min. [29]; hot-pressing with a force less than 30kN at 150 °C for 20 min. [13]; oven-drying for 48 h at 60 °C [18]; and convection oven drying at a temperature of 70 °C for 5 to 10 h [15]. The effect of drying methods on the properties of MBCs has been scarcely reported by researchers. However, Manan et al. [25] noted that the mechanical properties of MBMs are affected by the pressing temperature. The properties of hot-pressed composites of P. ostreatus- rapeseed straw relative to cold-pressed MBCs were compared by Appels et al. [13]. It was observed that hot pressing increases the strength and stiffness of the MBCs.

3.2.8. *Finishing processes*

Finishing operations are usually applied to MBCs to improve the aesthetic properties, seal surface pores and protect the surface from water and micro-organisms in the service condition [10]. The application of diverse coatings and re-growth of the MBMs constitute the major finishing operations carried out after the production of MBCs [10]. Depending on the service condition where the MBC would be applied, different types of coatings such as resins, natural oil, linseed oil, shellac, coconut oil, carnauba wax, or beeswax have been used to improve the surface properties of MBCs [7,29]. The comprehensive fabrication technique of MBCs according to several recent authors is given in Table 1. Table 1 compares the key physical and mechanical properties of MBCs to those of conventional construction materials.

4. Material properties of Mycelium-based composites

Mycelium-based biocomposites have grown in importance because of their economic, sustainability, and material characteristics. This is expressed by their unique range of properties which is dependent on the type of substrate used in producing them and their bio-fabrication routine. Mycelium composites' poor mechanical properties are frequently attributed to their mycelium content [39,40]. Recently research was carried out on the tensile strength of chitin-glucan extracts that are obtained from mycelium and it was discovered that the obtained mycelium binder has a great strength (tensile strengths of up to 25 MPa [12] and up to 200 MPa for fruiting body extract [41]), implying that the fungal growth density is low, which limits mycelium binder amount as well as the interaction between mycelium binder and substrate filler. This is stated as the likely possible cause of poor mechanical characteristics obtained in mycelium composites. The fungus species used as a binder to disperse agro-based filler into mycelium biocomposites influences growth density and the degree of interfacial adhesion at the mycelium-substrate interface, which differs substantially by species and substrate [42], and appears to impact the material's mechanical characteristics.

Biological evolutionary processes determine how well a fungal species flourishes on any particular organic matter (substrate). Naturally,

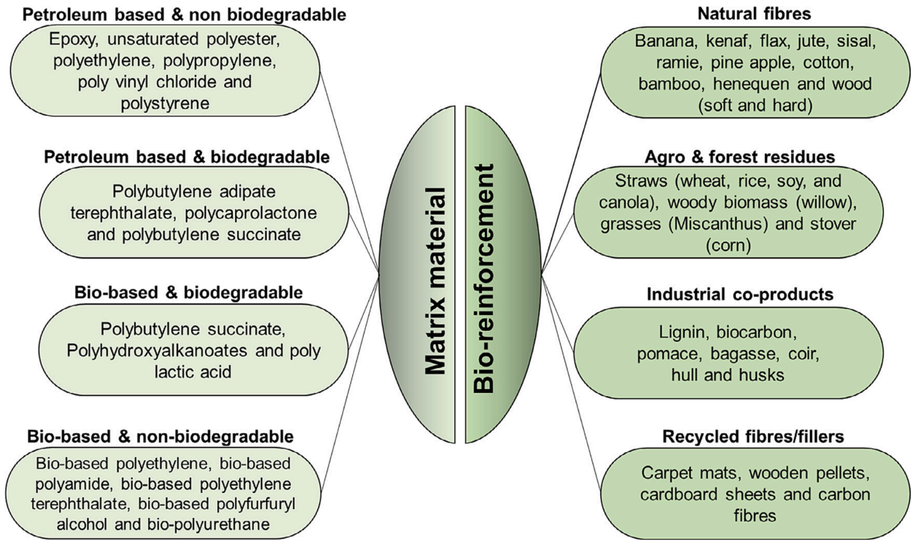

Fig. 4. Some conventional materials used for the fabrication of biocomposites versus the agro-based substrates for bio-fabrication of MBCs (Shanmugam et al. [16], culled with permission from Elsevier).

Mesophilic (optimum proliferation at moderate temperatures) micro-flora give way to thermophilic (optimum growth at elevated temperature) micro-flora. The Mesophiles flourish first when temperatures rise, absorbing simpler carbon providers (organic acids, sugars, and amino acids) and sparing only polysaccharide elements of biomass (cellulose as well as hemicelluloses) for the thermophiles. Several comparable instances may be seen in nature, such as rapidly developing primary colonisers swiftly eating accessible simple sugars, making both secondary and tertiary colonisers to be left with only more complex carbohydrates. This has resulted in natural preferences for these distinct carbon donors within these categories [43,44], which has a considerable impact on how effectively a fungus specie will thrive on any particular substrate. Because most mycelium-based biocomposites are cultivated on lignocellulosic agro-based by-products and waste materials, which usually lack ideal fungal essential minerals such as easily use simple sugars (glucose, sucrose, and fructose), white rot fungi (Ganoderma, Pleurotus genera, and phylum Basidiomycota, Trametes) are commonly used [12,34]. The mechanical characteristics of mycelium-based biocomposites are also influenced by the topology and structural network of the mycelium binder. An excellent example is mono-mitic hyphal, di-mitic hyphal, and tri-mitic hyphal networks that are obtained in basidiomycetes [45]. Basidiomycetes' hyphal networks can consist of up to three different hyphal varieties, binding, generative, as well as skeletal, with significant variances in the thickness of the cell wall, inner structure, as well as branching properties [45,46]. The mitic system is used to define the number of various hyphal kinds found within a species. Monomitic species have just generative hyphae, di-mitic species have two hyphal kinds often generative as well as skeletal, and tri-mitic species have all three hyphal forms [47]. Skeletal hyphae are thick-walled, usually solid, and they are sparsely branched or unbranched, whereas generative hyphae are thin-walled, hollow, and branching [12].

Binding (ligative) hyphae have strong walls, are usually solid, and are densely branched. Complex hyphal systems such as trimitic are generally thought to be more sophisticated than basic hyphal systems like monomitic [48,49,50], with the thickness of the wall of the hyphal system as well as the level of hydraulic content housed within their cells being accountable for specific characteristics of the biomass [51]. Although the tensile characteristics of fungal hyphae employed in fermentation have been investigated, with approximated hyphal ultimate tensile strengths (UTS) and elastic modulus of up to 24 MPa and 140 MPa respectively, the mechanical characteristics of wood-rot fungus hyphae are still not well understood [52,53]. The mechanical strength of generative hyphae (monomitic hyphal systems), which have hollow structure and possess cytoplasm, is thought to be diminished, with binding hyphae (di-mitic and tri-mitic hyphal systems) accounting for the material strength [54,55]. Although there is little data to back this up, mycelium biocomposites including Trimitic species like T. versicolor and multicolor have been observed to exhibit greater tensile strength (0.04 MPa) as well as flexural strength of about 0.22 MPa than the monomitic counterpart, such as P. ostreatus with tensile and flexural strength of 0.01 MPa and 0.06 MPa respectively [13]. It is also noted that when T. versicolor and P. ostreatus are grown on hemp, T. versicolor exhibits a stronger compressive strength than P. ostreatus, with compressive strengths of 0.26 MPa and 0.19 MPa respectively [56]. However, the existence of natural polymers like chitosan and chitin is restricted to the thin hyphal cell wall, which also appears to contain polysaccharides (mannose, fucose, and galactose), lipids, proteins, phosphate, and mineral salts [12,57]. This makes it difficult to emphatically state without being skeptical of the significance of the hyphal structure, with mycelial (binder) volume more likely to affect the mechanical performance level. The mechanical and physical characteristics of MBCs are discussed in this section of the review.

4.1. Density

MBCs have numerous advantages over conventional building materials, one of which is low density [1]. The density of most MBCs in literature lies in the range of 110–330 kg/m^3 [58] while that of conventional construction materials such as cement and gypsum-based materials are in the range of 1800–1950 kg/m^3 [59] and 417–945 kg/m^3 [60] respectively. In general, for most cellular materials, higher Young's modulus and strength can be achieved by increasing the material density [61]. Studies have shown that factors such as the types of substrates, porosity, and processing methods (such as cold/hot pressing) have a great effect on the density of MBCs. It has been widely reported that the density of MBCs is highly sensitive to substrate composition [13,17]. For instance, it has been reported that the volume fraction of fibers, wood pulp, or hulks in the composition of the mycelium substrate increases with the density of the MBC product [17,23,62,63]. Elsacker et al. [10] reported that the processing technique affects the density of the final mycelium composite product. It was observed that the density of P. osteratus composite grown on rapeseed straw substrate that was processed by hot pressing (at 150 °C, and force < 30KN) was higher (390 kg/m^3) compared to 240 kg/m^3 obtained for the same composite when processed by cold pressing (at 20 °C for 20 min and dried thereafter). This was attributed to the lower porosity levels in the hot-pressed samples relative to the cold-pressed samples [13]. In another study, Gou et al. [64] investigated mycelium biocomposites reinforced with natural reinforcing particles (NRPs) (carbonated sand). The colonisation duration of mycelium biocomposites is influenced by the kind of fungus. The introduction of NRP as reinforcement had no impact on mycelium development, but it increased the density of the obtained mycelium-based biocomposites somewhat more than typical mycelium-based biocomposites. The produced mycelium biocomposites containing NRP (0%-37.5 wt%) had dry densities ranging from 0.310 to 0.413 g/cm^3. It was observed that with an increase in NRP concentration, the dry density of the obtained mycelium-based biocomposites rose proportionally. The obtained dry density of the P. ostreatus test sample increased from 0.325 to 0.413 g/cm^3, also for those of the O. radicata sample the dry density increased from 0.317 to 0.411 g/cm^3, and for the MF sample, the dry density increased from 0.310 to 0.398 g/cm^3. By comparing the density of the three mycelium biocomposites, P. ostreatus biosamples were observed to have the greatest density, trailed by O. radicata and marine fungal (MF) samples. The obtained variation in dry density might be attributed to the variable degrees of colonisation generated by the distinct lignocellulose-degrading enzyme systems [65,66] between white-rot fungus and MF. According to the CT data (Fig. 5), mycelium-based biocomposites cultivated by Pleurotus ostreatus containing 7.5 percent NRP show a dense distribution of porosity. Pores account for 11.71 percent of the total sample volume.

4.2. Thermal conductivity

Mycelium composites especially those grown on straw and hemp

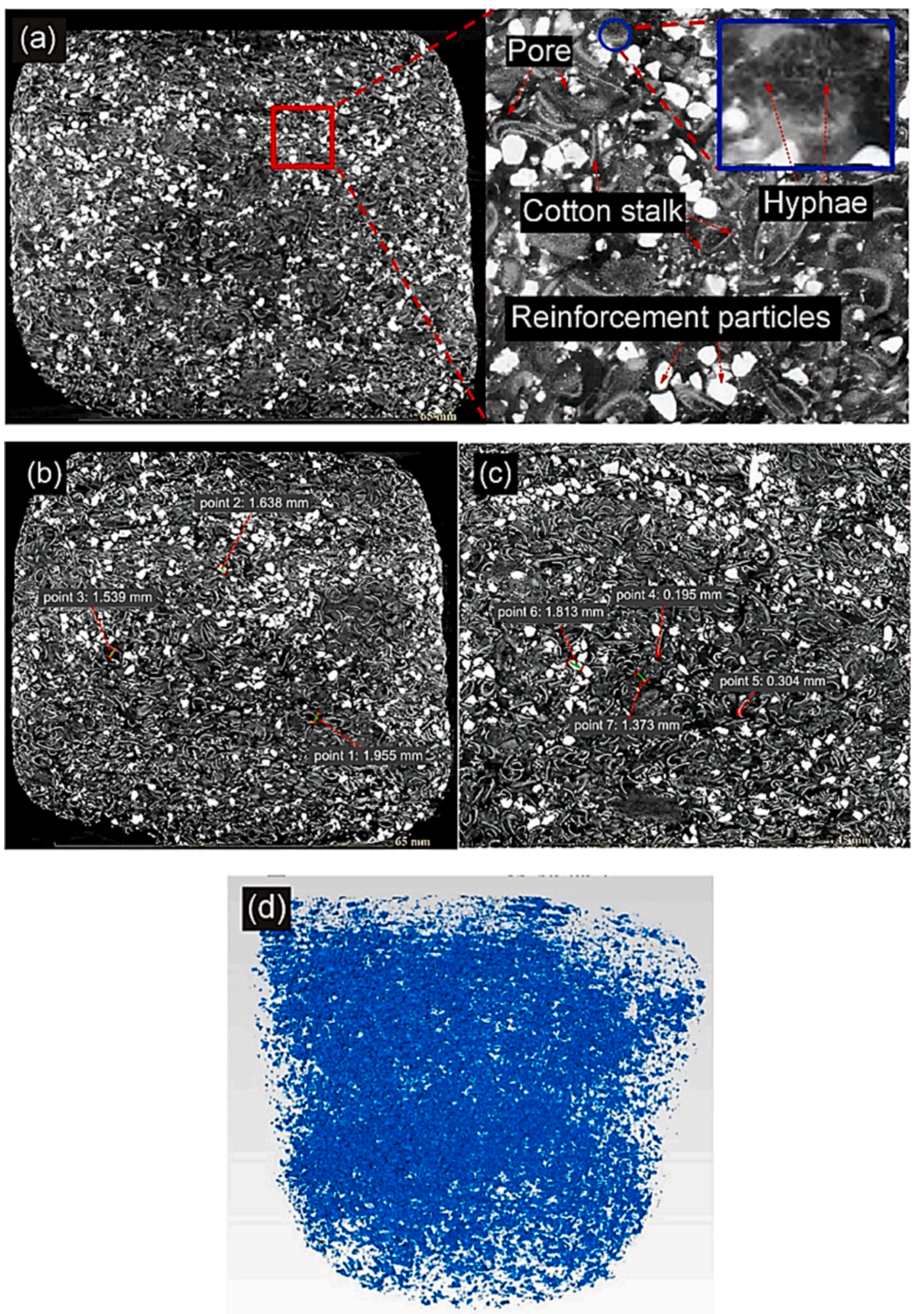

Fig. 5. CT photographs of the P-S2(7.5) mycelium biocomposites: (a) section diagram in the Y-Z directions, (b) distribution of pores and NRP in the X-Z directions, (c) distribution of pores and NRP in the X-Y directions, and (d) distribution map of total pores (Gou et al. [64], culled with permission from Elsevier).

have a porous structure with a characteristic low bulk fibre density which enables them to amass a considerable amount of air in-between the fibres, thereby acquiring insulation properties [12,67]. MBCs are thus considered natural thermal insulation materials since they possess low thermal conductivity, high porosity, low density, characteristic high moisture contents, and the presence of large amounts of air [25,68]. The thermal conductivity of MBCs has been observed to depend on the density of the composite, moisture content, and fiber type [12].

The investigation of mycelium composites made of different substrates including flax waste, straw, and hemp was carried out by [15]. Although higher thermal conductivity was recorded for the flax waste which was due to the high weigh-to-volume ratio of the substrate, nonetheless the three mycelium-based composite compositions resulted in better thermal insulation properties compared to existing materials. The hemp-based composite demonstrated the lowest thermal conductivity of all three substrates [15].

The thermal conductivity of several MBCs has been reported to fall within the range of 0.05 to 0.07 W/m.K which is similar or comparable to most prominent conventional insulation materials such as glass wool (57 Kg/m^3, 0.04 W/m•K), extruded polystyrene insulation (34 Kg/m^3, 0.03 W/m•K), sheep wool (18 Kg/m^3, 0.05 W/m•K) and kenaf (10 Kg/m^3, 0.04 W/m•K) [17,69]. Similarly, Xing et al. [70] carried out a study on a mycelium-based composite produced with wheat straw and three species of mycelium. They observed that the MBCs can serve as good thermal insulators following their low thermal conductivity (0.074–0.087 W/mK). Thus, MBCs have excellent insulation properties which enable them to compete with conventional insulation materials for thermal applications [69,71]. MBCs even have the potential to replace the existing conventional insulation materials products because of their comparatively lower cost advantage and biodegradable characteristics [12]. Sun et al. [72] studied the thermal conductivity of Trametes versicolor mycelium and yellow birch wood particles (substrate) biocomposite. The composites were incubated for up to 30 days. It was observed that the thermal conductivity obtained for the foam composites decreased with an increase in incubation time. This is understandable given that thermal conductivity closely corresponds with density in porous materials. The lower the density of the foam composite, the more air there is, which has a very low thermal conductivity property and this correlates to the reduction in thermal conductivity of the produced foam. After 30 days of deterioration, the density was reduced by around 10 percent, and the thermal conductivity was reduced by less than 10 percent, demonstrating that fungal degradation isn't an effective method for producing composites with low thermal conductivity properties. It would thus be more effective to make use of a substrate with inherent low thermal conductivity properties or to change the fabrication procedure to reduce the density of the foam structure.

Good insulating materials are known to possess low thermal conductivity, which is mostly related to the material's density. Biocomposite insulating materials help to lower buildings' environmental imprint [73]. Dias et al. [73] investigated the efficacy of a self-growing, biocomposite structural insulating material consisting of Miscanthus × giganteus as well as the fungus Mycelium. Various Miscanthus and Mycelium mix ratios were investigated to determine the best mixture for producing a porous composite with a reduced density. They carried out thermal conductivity tests on the various composite plates produced and it was observed that the thermal conductivity obtained for this novel material ranges between 0.0882 and 0.104 $Wm^{-1} K^{-1}$. These results are comparable to the thermal conductivity values of straw, hemp concrete, softwoods, and gypsum, which are approximately 0.08 [74], 0.1 [68], 0.12 [75], and 0.17 [75], respectively. However, when manufacturing costs and environmental implications are considered, the novel Mycelium-Miscanthus composite is less expensive to produce and has a much-reduced carbon footprint. Furthermore, fire resistance experiments on this novel Mycelium-Miscanthus composite plates without render were carried out. A ball of cotton wool was placed on the surface of the plate, and the test is regarded as complete when the cotton wool on the plate begins to burn, a gap or opening appears, or the existence of a sustained flame on the side facing away from the fire appears. After 40 min, a gap was seen, and the cotton wool began to burn. The Mycelium-Miscanthus plate is shown in Fig. 6 before and after it was burnt for 40 min. It was established that the Mycelium-Miscanthus composite plates fall within the category EI15 under the EN13501-2:2003 standard. The findings were reported to be adequate for developing a renewable insulating material out of Miscanthus and Mycelium. Fig. 7 depicts the temperature trend recorded by the thermal camera when the fire experiment was carried out. It was observed that the heat from the flame took approximately 7 min to reach the top of the plate and another 33 min to burn the cotton wool on the plate and create an aperture on the top of the plate.

Gou et al. [64] provided the thermogravimetric analysis findings for unreinforced mycelium biocomposites as well as mycelium-based composites containing natural reinforcing particles (NRPs) (carbonated sand). These findings were compared to the thermogravimetric study of EPS reported by Bruscato et al. [65]. The unreinforced mycelium biocomposites showed three stages of mass loss that were consistent with other research reported in the literature [72,76]. These stages have already been linked to mycelium water evaporation [77], thermal breakdown of lignocellulose [78], as well as indecomposable residual products of lignocellulosic fibres [79]. In comparison to the ones without NRP, the mycelium-based composites reinforced with NRP had more inflection points as well as less mass loss during the test. Thermogravimetric studies revealed that when the temperature was between 150 and 500°Celsius, the breakdown rate of the mycelium-based composites reinforced with natural reinforcing particles was lower. This discovery may be explained by the fact that the natural reinforcing particle is high in calcium carbonate (CaCO3) (95.85percent), and by the fact that the endothermic reaction takes place at high temperatures [80], which slows the decomposition rate of mycelium-based composites. The thermal stability of mycelium biocomposites was lower than that of EPS, while the residual mass was larger. However, at high temperatures (400 °C), it outperformed EPS as an insulating material. In a similar study, Jones et al. [34] investigated the thermal decomposition of mycelium-based composites cultured on high silica-based wastes (rice hulls and glass fines) and wheat grains. It was observed that the presence of high silica-based wastes improved the thermal degradation characteristics of the mycelium-based composites. As a result, the presence of CaCO3 or SiO2-rich materials can increase the thermal degradation resistance of mycelium-based biocomposites.

4.3. Water absorption rate

The water absorption rate is determined by the difference between the (dry) weights of the MBCs and weights after a pre-determined period of exposure to moisture [14]. The thickness of MBMs increases in response to water absorption thereby degrading the mechanical strength and properties of MBCs [81]. The water absorption rate of MBCs is one of the key application properties required in the design for the commercialization of mycelium-based products especially in structural applications such as building and construction [1]. The durability of MBCs in applications where they are likely to come in contact with moisture such as in construction materials depends on its rate of water absorption [15]. Many researchers including Elsacker et al. [15], Appels et al. [36], Soh et al. [82], and Ziegler et al. [83] have observed that the water absorption rate of MBCs varies depending on the type of substrate used in the synthesis of the MBCs. Elsacker et al. [15] studied the properties of MBCs synthesized from different types of substrates. It was noted that the water diffusion coefficient of MBCs is influenced by the density of mycelium fungal skin. The water absorption rate was observed to decrease as the density of the outer hydrophobic mycelium layers increased. MBCs obtained from hemp substrates produced denser outer hydrophobic mycelium layers compared to those obtained from flax and

Fig. 6. Plate without render subjected to fire test (a) before starting to burn (b) after 40 min (c) bottom of the plate after 40 min (Dias et al. [73], culled with permission from Elsevier).

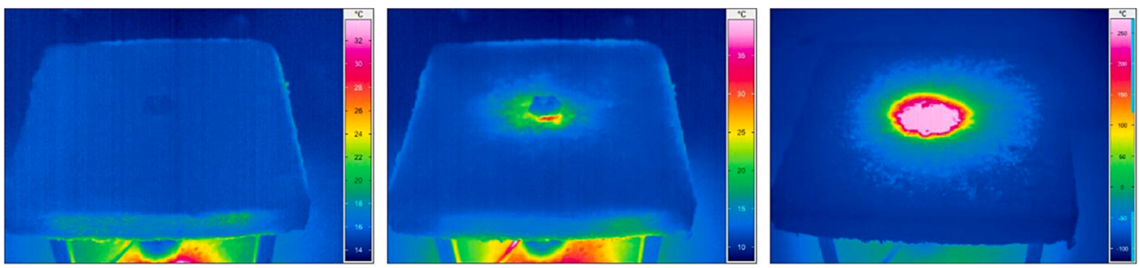

Fig. 7. Temperature progression during the fire test (a) before starting to burn (b) after 7 min (c) after 40 min. (Dias et al. [73], culled with permission from Elsevier).

straw substrates. This result suggests that MBCs manufactured from hemp substrates are potentially more suitable for applications in the building and construction industry because they have superior water absorption properties compared to MBCs obtained from flax and straw substrates. Mycelium products processed by pressing the mycelium biomass were observed to exhibit a lower rate of water absorption compared to MBCs that were processed by drying the fungal skin [83].

Gou et al. [64] investigated the water absorption and permeability of mycelium biocomposites reinforced with natural reinforcing particles (NRPs) (carbonated sand). It was noted that the water absorption properties of reinforced mycelium biocomposites were comparable to the unreinforced biocomposites. The author established that the presence of NRP reduces the permeability coefficient of mycelium biocomposites, and the mechanism behind this lowered percentage is associated with hyphal growth. Mycelium biocomposites with NRP (0–37.5%) had permeability coefficients that were comparable to silt, ranging from 2.81×10^{-5} to 5.28×10^{-6} cm/s. According to the findings of the experiments, the presence of hyphae has a great influence on the water absorption as well as permeability of the produced mycelium. In the test for water absorption at 168 h, it was observed that the more intense the hyphal development, the larger the mass increment and the permeability coefficients. Regarding water absorption rate, more hyphae development may lead to greater porosity, which promotes capillary action and hence increases water intake. [84]. For mycelium permeability, the hydrophobic properties of hyphae sped up hydraulic penetration and lowered drag force together with the substrate filler materials and water interface [85], resulting in mycelium biocomposites cultivated with P. ostreatus and O. radicata having a greater permeability coefficient than those cultivated with Acremonium sp., a marine fungal strain (MF) belonging to mold.

4.4. Acoustic absorption properties

MBCs are regarded as materials with high acoustic noise absorption properties because they can convert a considerable amount of mobile air molecules moving in sound waves into mild heat thereby impeding noise accumulation in an enclosed space [12]. The acoustic absorption capacity of some MBCs such as mycelium composites grown on rice straw (52 dBa), hemp pith (53dBa), and flax shive (53.5 dBa) are superior when compared with those of the conventional absorbers such as commercial ceiling tiles (61 dBa), urethane foam board (64 dBa) and plywood (65 dBa) [12]. Pelletier et al. [86] observed that the acoustic absorption properties of mycelium-based materials are sensitive to substrate composition. It was noted that the acoustic absorption rate of various substrates including switch-glass, rice straw, sorghum stalk, flax shive, kenaf, and hemp substrates lie in the range of 70 to 75% at an absorption frequency of 1000 Hz. Various factors such as particle porosity, tortuosity, flow resistivity, and pressing conditions have been reported to influence the acoustic performance of MBCs [87]. Owing to the porous and fibrous nature of MBCs, they possess a characteristic low inherent absorption frequency (<1500 Hz) which exceeds that of most commercial absorbers such as polystyrene and ceiling tiles in noise reduction [88]. The excellent acoustic absorption properties exhibited by MBCs are the main reason why they have been recently utilized in the production of sound insulation of walls, doors, and ceilings of concrete halls, as well as broadcasting studios [12,89]. Sun et al. [72] studied the acoustic absorption properties of T. versicolor mycelium and yellow birch wood particles (substrate) biocomposite. The biocomposite foam was cultured for up to 30 days. The sound absorption coefficient of the produced biocomposite foams in the 1000–6000 Hz range is shown in Fig. 8. The maximum values obtained for the sound absorption coefficient curves were all greater than 0.5 for all composite samples. Surprisingly, the composite with the lowest incubation time had the best sound absorption capability. The sound absorption coefficient rose with

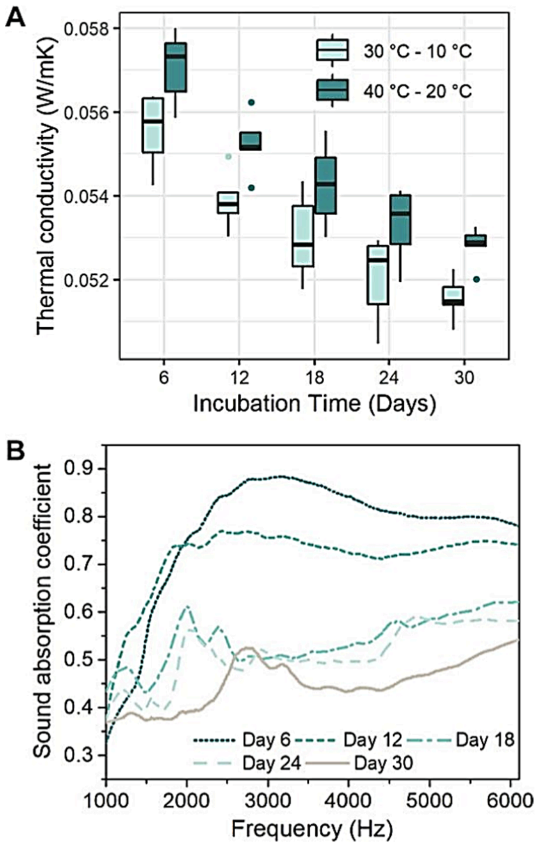

Fig. 8. Thermal conductivity (A) and sound absorption coefficient (B) of as-grown foams (Sun et al. [72], culled with permission from Elsevier).

sound frequency in general. The greatest sound absorption coefficient for the Day 6 foam was 0.87 at 2800 Hz, although they were all observed to be higher than 0.8 at higher frequencies. Sound absorption reduced as incubation time increased. The Day 12 sample followed the same pattern as the Day 6 sample but with a lower peak (0.76). The coefficient was substantially lower in the bulk of the frequencies over 1500 Hz in the Day 18, 24, and 30 data. The maximum readings were 0.61, 0.56, and 0.53, in that order. Day 6 and Day 12 featured just one large peak, although other lesser peaks occurred in different zones that were not within Day 6 and Day 12. The density obtained for Day 18, 24, and 30 test samples were observed to be lower than that of the starting sample (without incubation) and Day 6 test sample, and it was noted that the porosity was greater, as predicted. During the incubation process, the variations observed in the sound absorption coefficient were attributed to the ensuing changes in pore sizes between the wood particles [90]. The wider pores that are in between the wood particles allowed more air vibration to occur within the sample during the early stage of the incubation because the mycelium had not yet completely colonised the huge crevices between the wood particles. The successive development of the mycelium reduced the air pathways at the interparticle scale, lowering the pore diameter gradient and mean pore size and resulting in a decreased air viscosity ramp during sound energy transmission [91,92]. Simultaneously, it has previously been discovered that both mycelium-bonded composites and pure mycelium foams improved sound absorption at lower frequency ranges [86,88]. A similar pattern was observed in Day 12, 18, and 24 samples, however, it was paired with a significant reduction in sound absorption capabilities at a much higher frequency range. A hybrid system made of several materials might be one strategy for achieving greater sound absorption capabilities at all frequencies.

4.5. Compressive strength

Compressive strength measures the ability of material to resist the direct pressure of applied compression force, thus is a vital property for assessing the use-ability of materials in the building and construction sector. Several factors have been noted to influence the compressive strength of MBCs, such as the composition of the substrate, type of fungal strain, processing method, porosity, and degree of pressing [13]. Many authors including Ghazvinian et al. [9], Zimele et al. [14], Elsacker et al. [15], and STOWA [93] have determined the compressive strength of MBCs developed from various substrates. Zimele et al. [14] investigated mycelium-based biocomposites as building materials. The compressive strengths of hemp mycelium composites and wood mycelium composites were determined to be 0.36 MPa and 0.52 MPa respectively, and these values were found to be comparable with the compressive strength of conventional building materials such as cemented wood wool (0.3 MPa) and hemp concrete (0.36 MPa). Elsacker et al. [15] observed that the compressive stiffness of MBCs varies depending on the type of substrate as follows: chopped hemp (0.77 MPa), loose hemp (0.51 MPa), chopped flax (1.18 MPa), flax waste (0.31 MPa), loose flax (0.28 MPa) and wood (0.14 MPa). Ghazvinian et al. [9] reported a compressive strength of 1.1 MPa and 0.17 MPa for MBCs obtained from wheat straw and oak sawdust substrates, respectively. Similarly, STOWA [93] obtained 0.21 MPa for hemp, 0.43 MPa for cellulose mixed with hemp, 0.19 MPa for cellulose mixed with straw, and 0.24 MPa for cellulose mixed with wood. These results confirm that the compressive strength of MBCs varies with substrate composition. Haneef et al. [6] explained that the microstructure of mycelium-based materials depends on their feeding substrate which in turn influences their mechanical properties. Processing techniques have been reported to influence the compressive strength of MBCs as hot-pressed mycelium products showed higher compressive strength (0.43 MPa for cellulose mixed with hemp composites) compared to cold-pressed samples (0.27 MPa) [92]. It has been suggested that the strength of MBCs can be improved by increasing the bond between the substrate and the mycelium network [19]. Javadian et al. [2] reported that the compressive strength of MBCs can be increased by appropriate selection of the growth substrate. For instance, the compressive strength of mycelium P. ostreatus composite grown on wheat straw substrate increased from 0.02 to 0.15 MPa when grown on white oak sawdust substrate [33].

Some investigators have looked at modifying the composition of substrates to improve the mechanical characteristics of mycelium biocomposites. Ghazvinian et al. [9] fostered mycelium-based biocomposites produced on white oak sawdust as well as wheat straw substrates, discovering that the obtained compression strength of mycelium-based biocomposites cultivated on sawdust was nearly 6.5 times higher than those that were cultivated on wheat straw. Also, Travaglini et al. [94] synthesized mycelium-based biocomposites from red oak sawdust and discovered that sawdust substrates have higher compressive strength (1 MPa) than straw substrates. In a similar study, Yang et al. [17] developed mycelium-based biocomposites on natural fibre substrates and discovered that the inclusion of natural fibre had a beneficial impact on compressive strength (570 kPa) and the elastic modulus (60 MPa). According to these findings, it is deduced that when there is an increase in the substrate filler's stiffness, the mechanical characteristics of as-grown mycelium-based biocomposites tend to increase. In a recent study, Gou et al. [64] investigated the compressive strength of as-grown mycelium biocomposites and mycelium biocomposites reinforced with natural reinforcing particles (NRPs) (carbonated sand). P. ostreatus-cultured mycelium biocomposites showed maximum compression strength, trailed by O. radicata and marine fungus. For the identical fungus, the mechanical characteristics of the mycelium biocomposites improved with increasing NRP concentration. In unconfined compressive strength (UCS) testing, mycelium-based biocomposites cultivated with the use of P. ostreatus and 37.5 percent NRP exhibited the maximum compression strength as well as

Young's modulus which were obtained to be 508 kPa and 48.5 MPa, respectively, and its cohesion as well as friction angle were observed to be 78 kPa and 21.8° based on triaxial tests. The presence of natural reinforcing particles alters the failure mechanism and stress–strain behaviour of mycelium-based biocomposites as well. Under both unconfined and triaxial circumstances, the mycelium biocomposites failed in two ways: protrusion failure and shear failure. When the NRP concentration of mycelium biocomposites exceeds 22.5 percent for P. ostreatus and O. radicata, or 30 percent for marine mushrooms, the failure mode is a shear failure, and the stress–strain behaviour is strain softening. It was observed that when the NRP concentration is smaller, the protrusion failure mechanism is more common in mycelium-based biocomposites. The introduction of NRP enhances the material's cohesiveness and internal friction angle greatly. As a result, the presence of NRP increases the mechanical characteristics of mycelium biocomposites. Even though the compression strength of the mycelium biocomposites did not rise as much as that of mechanically processed mycelium biocomposites. The mycelium biocomposites made using this technology have a simple manufacturing programme, resulting in cheap costs. Given the physicomechanical qualities of mycelium-based biocomposites, they have the potential to be employed as lightweight backfill materials, which are in high demand in geotechnical engineering. In recent times, expanded polystyrene (EPS) composite soil (EPSCS), which is typically composed of soil, water, a binder (usually cement), and EPS, has been widely used as a lightweight backfill material, for example, when building roadway embankments, backfilling behind retaining walls and backfilling pipeline trenches, and bridge abutments [94]. EPSCS has a density of 500–1800 kg/m^3 as well as a compressive strength of 50–550 kPa [95]. Existing research indicates that as-grown mycelium-based biocomposites have a reduced density (160–280 kg/m^3 [17]), and compressive strength of 350–570 kPa [17], making them an excellent alternative for lightweight backfill materials employed in geotechnical engineering. Furthermore, there is no question that it is an environmentally beneficial substance that does not pollute the environment and effectively consumes agricultural leftovers.

4.6. Flexural strength/Modulus of rupture

Flexural strength which is also known as bend strength modulus of rupture can be determined by measuring the maximum bending stress that a material can sustain before it yields, and can be obtained from equation (1) [96].

$$f_m = \frac{3F_{max}l_1}{2bt^2} \tag{1}$$

where f_m is the bending strength (MPa), F_{max} is the maximum load at yield point or breakage (N), l_1 is the distance between the centres of the supports (mm), b is the width of the test sample (mm) and t is the thickness of the test sample (mm). The bending strength of MBCs was observed to vary with substrate composition. For instance, the bending strength of Ganoderma (fungal species) composites grown on a mixture of cellulose and hemp substrates was greater than the bending strength of the MBCs grown on straw substrates but less than the bending strength of the MBCs grown on a mixture of cellulose and wood substrates. Similarly, the bending strength of MBCs produced from straw substrates is higher when compared to that produced from a substrate containing a mixture of cellulose and straw [96]. In a related study, Tudryn et al. [97] reported that composites of cotton fiber have lower flexural properties when compared to fibrous straw-based composites (with flexural stiffness and strength in the range of 1 to 3 MPa and 0.06 to 0.22 MPa respectively). Composites of beech sawdust substrate were found to exhibit relatively superior properties with flexural modulus and strength of 9 MPa and 0.29 MPa respectively, which was attributed to their high density of mycelium hyphae network and continuous matrix phase microstructure formed on the composite surface. In another study, Sun et al. [72] observed that 2.5% of nanocellulose additive to wood particle substrate can increase the flexural strength of the product from 1.5 to 3.5 MPa.

It has been reported that the flexural or bending strength of MBCs can be influenced by several factors among which include: porosity (with a negative correlation), density (positive correlation), and mycelium particle size [98]. The modulus of rupture of MBCs has been observed to increase with incubation time. It was explained that the density and intensity of the mycelium hyphae network bonding on the substrate increases with the incubation duration thereby increasing the modulus of rupture of the mycelium-based material [19]. It was also observed that *P.* osteratus composites grown on rapeseed straw and processed by hot pressing developed a flexural strength of 0.87 MPa when compared to 0.21 MPa that was obtained for samples that were cold pressed [2]. It was explained that hot pressing improved the mechanical properties of mycelium through the mechanism of densification and reduction of porosity and moisture content [2].

4.7. Tensile properties

Tensile properties are among the best-considered material properties of MBCs [12]. Many authors including Jones et al. [12], Hassanzadeh et al. [99], and Ifuku et al. [100] have reported that the type of substrate is an important factor that influences the tensile properties of MBCs. For instance, the tensile strength of mycelium composites grown with sawdust substrate was higher (in the range of 0.05 to 0.18 MPa) compared to the range of 0.01 to 0.04 MPa obtained for composites grown with straw substrate [12]. The mechanical behaviour of Ganoderma lucidum (G. lucidum) and Pleurotus ostreatus (P. ostreatus) composites grown on pure cellulose and cellulose-potato dextrose broth substrates was reported by Haneef et al. [6]. The addition of potato dextrose broth to the pure cellulose substrate stimulates the biosynthesis of plasticizers (lipids, proteins) which in turn leads to an increase in the ductility of the MBCs. The ultimate strength of composites produced with G. lucidum fungal strain was higher when compared with P. ostreatus composites and this was attributed to the morphology and elasticity of the structure of composites produced from G. lucidum. This result suggests that the type of fungal species selected for biofabrication of MBCs affects their tensile properties. Javadian et al. [2] reviewed the application of MBCs in the construction industry and reported that processing methods affect the tensile strength of MBCs. It was observed that the tensile strength of P. osteratus composite grown on cotton seed hull substrate that was processed by hot pressing (at 150 °C, and force < 30KN) was higher (0 0.13 MPa) compared to 0.03 MPa obtained for the same composite when processed by cold pressing (at 20 °C for 20 min and dried thereafter) [13]. Fig. 9 shows the effect of hot and cold pressing techniques on the strength of MBCs. It can be deduced from Fig. 9 that the strength of mycelium-based products is strongly dependent on the processing technique as pressed mycelium samples were observed to be stronger than the mycelium products that were not pressed.

4.8. Elastic deformation

Elastic deformation is defined as the temporary deformation of a material shape that is self-reversing after removing the force or load. It is mostly expressed in terms of young modulus and shear modulus. Several authors including Haneef et al. [6], Appels et al. [13], and Yang et. al. [17] have reported that the type of feedstock used in the bio-fabrication of MBCs influences their modulus of elasticity. Appels et al. [13] observed that the elastic modulus of T. multicolor mycelium composite grown on Beech sawdust was higher (13 ± 0.5 MPa) compared to 4 ± 0.4 MPa obtained for T. multicolor mycelium composite grown on Rapeseed straw. An appreciable increase in the Young's modulus of MBCs was observed when chitin nanofibers additives were introduced to different substrate materials [99,101]. The addition of natural fibres in mycelium feedstock has also been reported to increase Young's modulus

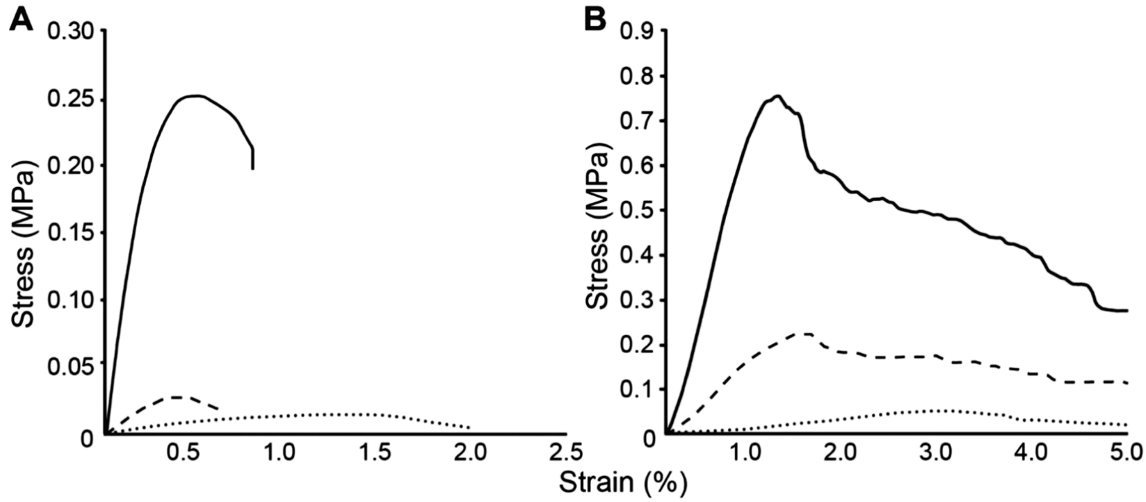

Fig. 9. Tensile (A) and bending (B) tests of P. ostreatus grown on rapeseed straw without pressing (dotted line), and cold (striped line) or hot (solid line) pressing (Appels et al. [13], culled with permission from Elsevier).

of MBCs [17]. In a related study Haneef et al. [6], observed a significant improvement in Young's modulus of P. ostreatus cellulose composite with dextrose additive into the growth medium compared with a composite of G. lucidum cellulose due to their morphology. It can thus be deduced from these studies that substrate composition significantly affects Young's modulus of MBCs. Appels et al. [13] observed that processing methods can be employed to tailor the elastic modulus of MBCs. It was reported that the elastic modulus of P. osteratus composite grown on rapeseed straw substrate increased from 9 $\pm$ 1.2 MPa (in cold pressed condition) to 97 $\pm$ 9 MPa after hot pressing at 150 °C [13].

Water absorption of MBCs has been observed to be relatively high compared to conventional construction materials such as cement or plastics and this reduces their strength and limits their application in construction [50]. However, the utilization of MBCs in construction industries may thrive in tropical regions due to the characteristic low relative humidity which limits the absorption of water [40]. MBCs have relatively low compressive strength compared to cement but have an overriding advantage of lightweight [1]. It can be deduced from the data displayed in Table 1 that the specific compressive strength of MBCs is higher than that of cement. Specific compressive strength refers to the ratio of the compressive strength to the density of the material [107]. This observation therefore suggests that MBCs have great potential for commercial utilization in the construction industry, especially in the tropical regions.

5. Applications of mycelium-based composites

5.1. Building and construction

The supposed use of mycelium-based composites in the construction industry is mainly due to their unique properties including fire-proof, thermal insulation, and acoustic absorption properties [26]. Several reviewed papers have shown improved material properties of mycelium-based composite suitable for building and construction activities [2,10,12]. Furthermore, MBCs have been widely reported to exhibit superior fire safety features compared to conventional building materials such as polystyrene insulation and particle board [108]. Jones et al. [34] emphasized that MBCs are safe compared with conventional high-inflammable petroleum-based building materials because they release less smoke and carbon (IV) oxide during combustion. Jones et al. [12] reported that MBCs have a much longer duration of flashover (311 – 370 s) compared to 173 s and 61 s reported for particleboard and polystyrene insulation foam respectively. Heat release rate (HRR) is a material property that determines the rate of fire growth and spread during combustion [109]. Interestingly, MBCs have been observed to possess lower peak HRR (185Kw/m^2) compared to 503 Kw/m^2 and 200 Kw/m^2 obtained for polystyrene insulation foam and particleboard respectively [12]. MBCs possess superior termite resistance properties when compared to conventional building materials [25].

Concerted efforts have been made by researchers very recently on bio-designing, development, and characterization of the physical, chemical, and mechanical properties of mycelium-based materials with the view to maintain a clean environment, replace the expensive and non-biodegradable synthetic construction materials, and transform the future of the construction industry through the concept of bio-fabrication and bio-economy [2]. MBCs have been reported to exhibit excellent termite-resistant properties in addition to their characteristic low densities (or lightweight), fire safety, and acoustic damping properties [12]. Thus, they have been considered viable alternatives or options to replace conventional construction and building materials in applications such as polystyrene insulation and particle- board, furniture, walls, and ceiling tiles [12,26]. In a related study, Yang et al. [5] noted that mycelium-based foams and sandwich composites are recently being developed for building and construction materials as both semi and non-semi structural materials to replace the conventional materials (plastic films and sheets, synthetic foams and plastics) for paneling, flooring, furniture, and decking. Companies such as MycoWorks, Mycotech, NEFFA, MOGU, and Ecovative Design have played a vital role in the designing and production of mycelium-based composite products for different uses [2]. Therefore, the commercial utilization of MBCs in building and construction in various applications such as acoustic and thermal insulation, paneling, and drywall as well as in door panels and window frames is expected to override the synthetic construction materials soon [2]. Fig. 10 is a conceptual presentation adapted from Manan et al. [25] of some typical products developed by MBCs in various areas of applications including building and construction. Some of the specific mycelium-based products developed for building and construction applications are reviewed in the rest of this section.

5.2. Mycelium-based composite products in the building and construction industry

5.2.1. Mycelium bricks

The compressive strength and weight per cubic metre of mycelium brick are about 30 psi and 43 kg ($\approx$ 0.7 psi/kg) respectively, which is very low when compared to 4000 psi and 2400 kg ($\approx$ 1.7psi/kg) respectively obtained for concrete [110]. Thus, it can be inferred that the specific compressive strength of mycelium bricks is proximate to that

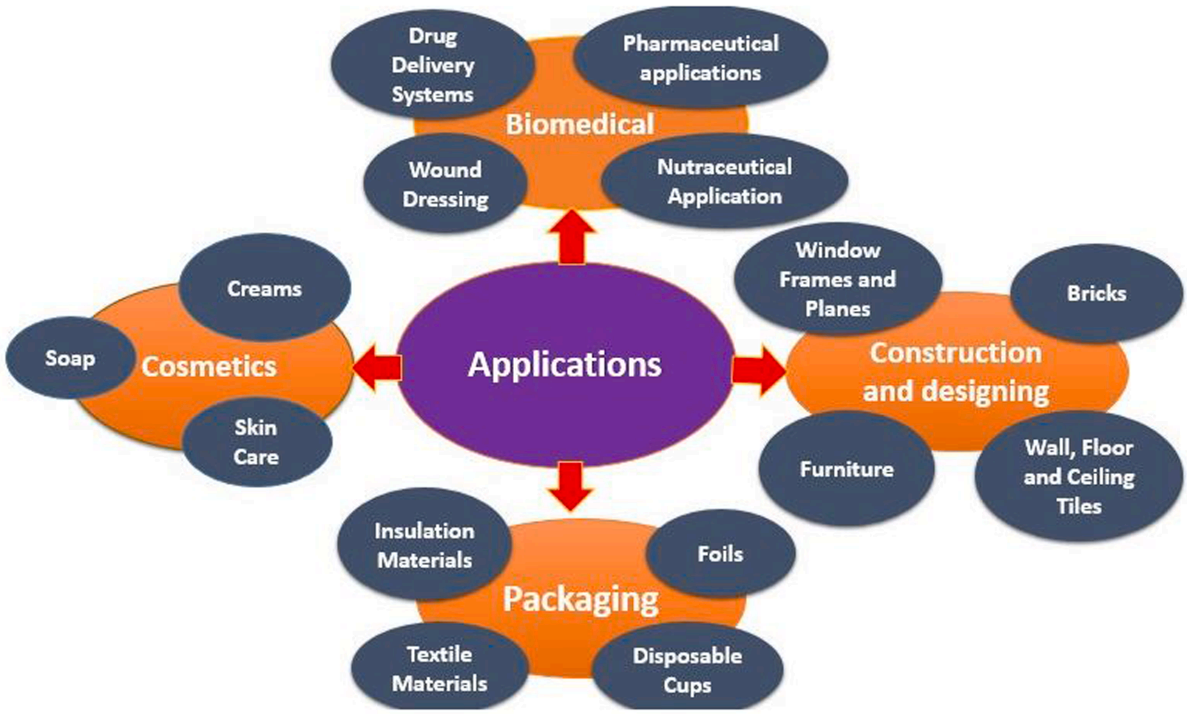

Fig. 10. Conceptual presentation of some specific products developed from MBMs for various applications.

of concrete. Low thermal conductivity is another vital property considered when selecting a brick material for building and construction. Mycelium bricks (with thermal conductivity ranging from 0.09179 to 0.1534 W/mk) have been reported to show better thermal insulation performance than resin-based materials [48]. Similar values of thermal conductivity ranging from 0.074 to 0.087 W/mk have been reported for Oxyporus (OXY) [48]. In another study conducted by Kshitij et al. [110], it was shown that bio blocks exhibited improved thermal stability, hydrophobic properties, and mechanical strength. The study maintained that the compressive strength of bio blocks developed from P. ostreatus mycelium grown on various agricultural residue substrates (such as wheat bran, sugar cane, sawdust, and their mixture) lie in the range of 6.0 to 7.5 N/mm^2. The mix substrates had the highest strength (7.5 $\pm$ 0.3 N/mm^2) with sugar cane having the least strength (6.0 $\pm$ 0.3 N/mm^2) due to its relatively larger particle size leading to poor mycelium penetration and surface coverage of sugar cane bio blocks. A 13-metre-tall tower known as "Hy-Fi" was constructed with 10,000 mycelium bricks by mixing a wooden beam with mycelium-based composites to improve the strength [111,112]. In 2014, the project when presented won the Young Architects program competition at "MoMA PSI" in New York [110,112].

5.2.2. *Mycelium insulation panels*

The current regulation to solve the global challenge of greenhouse gas emissions has prompted industries and researchers to explore carbon capture, to make the Earth more sustainable [1]. The increasing world population has resulted in increased production of goods, increased need for renewable energy, and corresponding escalation in the need for materials for thermal insulation [1]. To address these challenges, regulations have been imposed which have resulted in the development of various measures or approaches to curb carbon footprint in every aspect of industry [68]. Against this background, mycelium-based composites for thermal insulation are now being considered [1,17]. Polymers like polyurethane and polystyrene are among the conventional materials utilized over the years for thermal insulation because of their poor thermal conductivity and high specific heat capacity, nevertheless, the expense of recycling them due to high energy consumption, non-degradability and environmental hazards are persisting problems [1,6]. The utilization of MBCs for thermal insulation is envisaged and will provide a solution to these problems considering their biodegradable nature and high specific heat capacity alongside low thermal conductivity and low density (Table 1). Also, MBCs are good absorbent, insulation, and fire-resistance materials due to their filter-like structure and porous attributes [113]. Hence, mycelium composite panels can be used in filtration systems and as a good adsorbent of atmospheric particulate matter. Taekyoung and Jaeyun [76] developed P. ostreatus mycelium composite panels grown on four different substrates such as hemp stalk, rice straw, lacquer tree wood chip, and oak wood chip, using $NO_3{}^-$ and $SO4^{2-}$ to measure the particulate matter adsorption performance. It was observed that mycelium composite panels have a higher $NO_3{}^-$ and $SO4^{2-}$ adsorption than puncheon granite panels. Hemp-based mycelium composite panels had the highest $NO_3{}^-$ adsorption, rice straw had the highest $SO4^{2-}$ adsorption while lacquer tree wood chip-based panels had the least $NO_3{}^-$ and $SO4^{2-}$ adsorption. In a related study, Kimberley et al. [114] reported the development of a mycelium panel made of wheat husks and reishi substrates having temperature and relative humidity of 25 °C and 85% respectively when grown for three weeks with Ganodermalucidum as a binding agent. The mycelium panel was observed to exhibit good sound insulation capacities.

5.2.3. *Mycelium furniture*

The possibility of producing mycelium-based composite furniture in buildings by mixing nature with technology has become a reality. Holt et al. [22] noted that all classes of materials have witnessed the application of three-dimensional (3D) printing technologies (an additive manufacturing process that creates a physical object from a digital design) in other to produce different shapes and structures. Gantenbein et al. [37] printed 3D living complex materials using hydrogels inoculated with Ganodermalucidum mycelium. They reported the possibility of exploiting 3D technology in the development of biomaterials with the ability to regenerate and adapt to changing environmental conditions. Erick Klarenbeek a Dutch designer produced a mycelium chair with 3D printing technology by using a powdered straw substrate, water, and living mycelium, that is, yellow oyster mushroom [115]. It was explained that the mycelium chair was produced by allowing mycelium to grow and consume the straw framework of the chair (bioplastic shell) [115]. The 3D printing technology is not limited to mycelium chairs alone but can also be used to produce tables, a whole interior, or erect a house [114].

5.2.4. Mycelium walls, floor, and ceiling tiles

The global sustainable development strategy is directed towards replacing non-renewable materials with bio-based materials to ensure a successful transition from a linear economy model to a sustainable bio-economy [116]. Consequently, MBCs are now being considered for applications involving ceiling tiles and walls because they possess excellent acoustic damping capacity, fire retardant properties, lightweight (or high specific compressive strength), and insulating properties that are comparable to those of conventional ceiling panels such as polystyrene and particle boards as shown in Table 1. MBCs have been successively utilized to manufacture ceiling panels, which have improved acoustic and fire-retardant properties to the conventional materials used for ceiling panels [117]. Mogu, a construction company based in Italy has designed and fabricated floor tiles made of MBCs in combination with different bio-based materials such as bio-based fibreboards [118]. The product consists of a bio-based fibreboard core with bio-polyurethane and oyster outer layer and a topcoat consisting of water-based paint [118].

Mycelium-based materials are very economical and have been reported to exhibit superior fire safety properties than traditional construction materials such as extruded polystyrene foam and particleboards [119]. Pelletier et al. [120] reported that acoustic tiles made of MBCs have comparable properties to commercial acoustic tiles. For instance, Pelletier et al. [120] noted that the density and acoustic damping capacity of mycelium tiles grown on agricultural by-products were 0.42 g/cm^3 and 7.1 respectively, which are comparable to 0.71 g/cm^3 and 7.6 respectively, obtained for a commercial acoustic tile. In a related study by Saez et al. [121] where a sandwich panel with mycelium composite mid-layer was developed, it was reported that MBCs are envisaged to compete favorably for selection in applications relating to sandwich wall and ceiling elements. This assertion was made in consideration of their several favourable properties including lightweight, low energy consumption during construction, thermal insulation, and acoustic insulation due to the sound-absorbing effect of the core layer of mycelial material. MBC tiles are expected to replace conventional plastic and ceramic tiles soon because they are eco-friendly, biodegradable, and relatively cheap [118].

5.2.5. Binder

Another vital role of mycelium in the construction industry is mycelium which serves as a binding agent to provide structural stability [12]. Mycelium binders are foam-like materials with lower densities and elastic moduli than pure mycelium which are derived from MBCs and used for bonding substrates [13]. Mycelium binders are recently being used as low-density adhesives to join two thin laminate facings in sandwich structures [122]. The structure of mycelium binder can affect the mechanical properties of MBCs [12]. Chitin-glucan extracts which serve as mycelium binders derived from mycelium have been reported to attain a tensile strength of 25 MPa [123]. The high tensile strength of the mycelium composites is a consequence of the high cellulose content in the mycelium matrix [30]. The bond strength of the mycelium-based material is determined by the binding power of mycelium which in turn depends on the fungi strain and the type of substrate) [1]. The compatibility of the mycelium matrix with the reinforcing substrate is due to the superdense network between the components [1]. Jiang et al. [40] studied the production of MBCs sandwich structures made by growing mycelium on agricultural residues. The study developed a bio-resin matrix using mycelium as a binding agent. Sun et al. [123] reported that mycelium binders are more reliable compared to other conventional wood composite binders. The mycelium served as the binding agent by substituting glues in engineered woods such as medium-density fiberboard (MDF) and helping hold wood fibers into sheets or molded forms without necessarily making use of glue [79]. Other applications of mycelium-based composites are in the field of biomedical applications such as drug delivery, and bio-sensing [124,125], packaging such as mycelium foam [51], and also cosmetic as moisturizer [126].

6. Challenges and future scope

6.1. Mycelium concerns and limitations

Bio-based materials such as Mycelium have a wide spectrum of technical properties and advantages that can be useful in developing materials and products that have green credentials (renewable and recyclable properties) and have the potential to contribute to net zero efforts and also, available as low-cost raw materials for a range of uses and product design. However, Mycelium materials, like all materials are likely to experience a range of challenges that can affect the performance of the material. Considering the status of available literature on Mycelium, there are some concerns and limitations as discussed below.

6.2. Varying mechanical properties

There are many studies (Haneef et al. [6], Appels et al. [13], Sydor et al. [26], Girometta et al. [127], Robertson et al. [128] and Ecovative [129]) on the potentials and advantages of mycelium as a candidate material to replace some of the conventional materials such as wood and plastics used for product design. However, different researchers have gotten varying results on the mechanical properties of mycelium-based products (Table 1). As already noted, studies indicate that the properties of the mycelium composites depend on the fungus specie, substrate, growth conditions, and processing of the material, as well as its additives [13].

It can be deduced from the reviewed articles that the material properties of mycelium-based composites and products may be altered to meet different demands by choosing the substrate type and fungal species, adjusting the growth circumstances, and changing the way the mycelium is inactivated once it has grown and dried. This level of customization has great potential but there is the need to be able to have standardized mechanical properties expected across the board. To have these standardized properties, there is a need for more R&D work.

6.3. Limited testing data

When developing new materials, testing and qualification of the materials is crucial, the material ultimately has to be tested against the specific environment and areas of application of the material. This qualification and performance data are critical and essential to demonstrate the consistent properties of a material. However, mycelium products are quite new and there is limited industry peer-reviewed testing data available.

Therefore, there is a need for universal testing requirements and published standards (ISO, ASTM) to ensure that qualification and testing programs can be developed to support the manufacture and use of mycelium in service.

6.4. Weathering and moisture

Mycelium, like other bio-based materials, is organic, which means it is vulnerable to damage by environmental factors and microorganisms ranging from moisture to bacteria to fungi. According to research, it has been observed that mycelium bricks cannot be employed for long-term buildings due to their diminishing resistance to water, humidity, as well as mould growth [13,128]. As the capacity to repel water declines over time, the mycelium-based bricks become more susceptible to mould and humidity. Based on the foregoing, the water absorption of the final mycelium-based material is a key source of worry in terms of quality and durability. Some researchers suggest that coating might be used to overcome this moisture retention challenge, but this will remain a limitation until further work can be done on mycelium materials.

6.5. Scalability

Mycelium structures are grown, rather than manually assembled, this unique manufacturing process makes it hard to say if or when mycelium-based materials will be produced on an industrial scale. Especially because different substrates and species of mycelium give different mechanical properties quotient [13]. Some companies like Ecovative and Mycoworks pioneered mycelium-based technology and have commenced some scaled production of mycelium materials but a lot of this work is for research and development purposes and also patent protected and therefore, not available in the public domain [129,130].

For Mycelium to achieve its potential and replace conventional materials, there will be a need for assurance of an adequate supply of raw materials (specific substrate and mycelium species) and available technology to support the manufacturing process.

6.6. The application question

Currently, there is a wide range of interest in mycelium and many individual research studies are ongoing as regards product application and new frontiers where mycelium materials can replace conventional materials. This development might slow down progress as regards being able to gather tests and qualifications that can help to standardize manufacturing methods and performance necessary to develop successful end products. Therefore, without a focused approach on what materials mycelium intends to replace and a targeted application function, research efforts will continue to be divergent.

7. Conclusion

Biocomposite materials that can help in the reduction of carbon emission and energy consumption of non-renewable and non-biodegradable materials used in building and construction industries, such as cement, concrete, metals, and polymers, are currently in high demand. The prospects of mycelium-based composites to meet this demand were appraised in this review through analyses of their biofabrication procedures, material properties (in comparison with traditional materials), and promise for use in building and construction applications. It was noted that mycelium-based composites have several advantages from technical, environmental, and green materials perspectives which make them desirable for building and construction purposes. However, their low mechanical properties, high water absorption, and as well as lack of standardized development methods, limit their applications to semi-structural and non-structural applications such as paneling, furniture, and decking. It is proposed that future research studies on mycelium-based composites should be focused on reconciling their varying mechanical properties, which are dependent on substrate, fungus specie, growth condition, and processing method. Limited testing data; weathering and hydrophilic propensities, and scalability, are other factors to be considered if they are to achieve long-term commercial success and applicability.

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.

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