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Engineered mycelium composite construction materials from fungal biorefineries: A critical review

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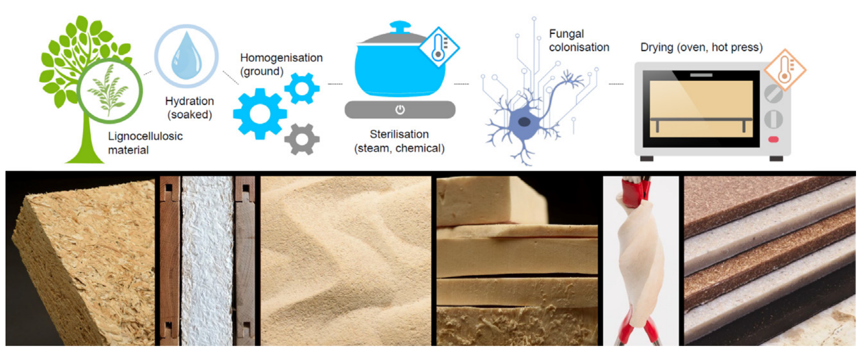
HIGHLIGHTS

- Fungal biorefinery upcycles by-products into cheap and sustainable composite materials
- Can replace foam, timber and plastic insulation, door cores, panels, flooring, furnishings
- Low in density and thermal conductivity, high acoustic absorption and fire safety
- Show particular promise as thermal and acoustic insulation foams

GRAPHICAL ABSTRACT



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ABSTRACT

Mycelium composites are an emerging class of cheap and environmentally sustainable materials experiencing increasing research interest and commercialisation in the EU and USA for construction applications. These materials utilise natural fungal growth as a low energy bio-fabrication method to upcycle abundant agricultural by-products and wastes into more sustainable alternatives to energy intensive synthetic construction materials. Mycelium composites have customisable material properties based on their composition and manufacturing process and can replace foams, timber and plastics for applications, such as insulation, door cores, panelling, flooring, cabinetry and other furnishings. Due to their low thermal conductivity, high acoustic absorption and fire safety properties outperforming traditional construction materials, such as synthetic foams and engineered woods, they show particular promise as thermal and acoustic insulation foams. However, limitations stemming from their typically foam-like mechanical properties, high water absorption and many gaps in material property documentation necessitate the use of mycelium composites as non- or semi-structural supplements to traditional construction materials for specific, suitable applications, including insulation, panelling and furnishings. Nonetheless, useful material properties in addition to the low costs, simplicity of manufacture and environmental sustainability of these materials suggest that they will play a significant role in the future of green construction.

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Contents

1. Introduction

Significant pressure has been applied to the construction industry over the past decade, as the supply of traditional construction materials, such as cement, bricks, timber, cladding and partitioning materials, has struggled to keep up with an ever-increasing global population [1,2]. Production of these conventional construction materials consumes energy, limited natural resources and pollutes our air, land and water [2]. Up to 36% of the lifetime energy demands of a typical dwelling can be attributed to the harvest or extraction of primary materials, manufacture, transport and construction of the building [3]. Low energy buildings, while using less energy during occupation, are even less environmentally sustainable to build (up to 46% of the lifetime energy demands of the dwelling can be attributed to the construction of the building), due to the energy required to manufacture the increased levels of insulation, higher density materials and additional technologies they utilise [4,5].

The rapidly growing global population has also resulted in growing food demand and increased agricultural output, leading to the generation of agricultural by-products and wastes, such as sugarcane bagasse, rice husks, cotton stalks, straw and stover. [6]. The combined biomass residue generation of India and south east Asia alone is as much as 1 billion tons every year [6,7]. Low-grade agricultural by-products and wastes have limited applications with their primary use being fertiliser, animal bedding and fillers for building materials and road construction but they are largely discarded as waste or burned, generating carbon dioxide and other greenhouse gases [8].

The vegetative growth of filamentous fungi (mycelium) has attracted increasing academic and commercial interests over the past decade as a new form of low energy bio-fabrication and waste upcycling [9–12]. Mycelium binds organic matter through a network of hyphal micro-filaments in a natural biological process able to be exploited to produce both low-value materials, such as packaging, and higher-value composite materials [9–11,13,14] from problematic agricultural and industrial waste materials with little or no commercial value [15,16]. This mycelium binder constituent interfaces a dispersed phase of agricultural residue (substrate filler) and functions as a load transfer medium between the typically fibrous agricultural residue within the composite in a manner similar to the matrix phase of a polymer composite [11,17].

Mycelium-derived materials have several key advantages over traditional synthetic materials including their low cost, density and energy consumption in addition to their biodegradability and low environmental impact and carbon footprint [13,18,19]. A wide variety of utilisable substrates coupled with controlled processing techniques (e.g. growth environment and hot pressing) allow mycelium-derived materials to meet specific structural and functional requirements including fire resistance and thermal and acoustic insulation [9–11,13]. This not only permits their use as waste-derived environmentally friendly alternatives to synthetic planar materials (e.g. plastic films and sheets) [13], and larger low density objects (e.g. synthetic foams and plastics) [10,11,20,21] but also as semi-structural materials (e.g. panelling, flooring, furniture, decking) [14,22–24], paving the way for new possibilities in environmentally sustainable construction. However, several factors limit the current application and usage of mycelium materials, primarily stemming from their typically foam-like mechanical properties, high water absorption and many gaps in material property documentation. These limitations make further research and development of these materials necessary in addition to targeted usage in specific applications, such as insulation, door cores, panelling, flooring, cabinetry and other furnishings.

2. Fungal biopolymers and the fungal biorefinery for composite production

Fungi are a natural and renewable source of valuable structural polymers, such as chitin and chitosan, as opposed to cellulose which is the main structural polymer in plant cell walls (Fig. 1). Chitin is a linear macromolecule composed of *N*-acetylglucosamine units and is also the main component of most insect and other arthropod exoskeletons [25]. It is strong with a nanofibril tensile strength of ~1.6–3.0 GPa [26] resulting from a high dipole moment and hydrogen bonding between the chains of the macromolecules [27].

Fungal cell walls are present in hyphae, which form a mycelium (collective noun) of hyphal filaments, comprising a thick and complex fibrous network of chitin, other polysaccharides, such as glucans, manno-proteins, chitosan, polyglucuronic acid or cellulose, and smaller quantities of proteins and glycoproteins [28,29]. These components result in mycelium exhibiting mechanical properties typical of lignocellulosic materials, such as wood and cork [30]. However, mycelium composites comprising a mycelium binder that interfaces a dispersed substrate filler phase of agricultural residue have lower densities and elastic moduli than pure mycelium and are generally classified as

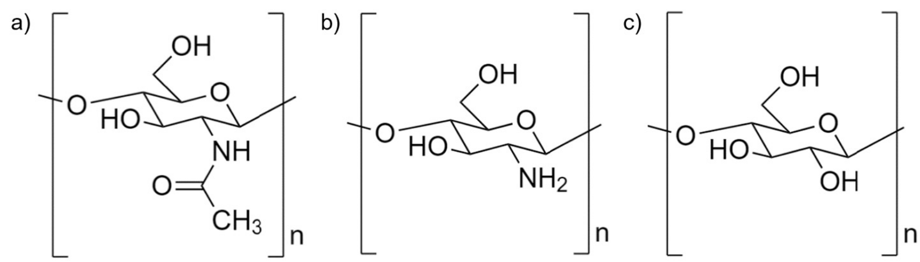

Fig. 1. Molecular structures of (a) chitin, (b) chitosan and (c) cellulose.

foams [31,32]. This is due to the amount of air contained within and between the often porous and loosely packed substrate filler [10].

Mycelium composites are manufactured using a low-energy, natural manufacturing process, which sequesters carbon and is one of the key advantages of these materials (Fig. 2). Raw material is required as a precursor and can realistically constitute any material that can sustain fungal growth, such as carbohydrates [9,33]. Low-cost lignocellulosic agricultural or forestry by-products or wastes are commonly used as fibrous substrates, such as straw, or particulate substrates, such as sawdust, to keep the cost of mycelium composites low and to facilitate waste upcycling and circular economy [11,34,35]. However, usage of these cheap, low-grade materials as substrates, while keeping costs low and environmental sustainability high, has the unfortunate side effect of limiting fungal growth and hence compromises the material properties of the composite. Although this compromise is acceptable for production of foam-like mycelium composites, higher grade and more expensive substrates such as nutritious wheat grains and saw dusts are sometimes used when mechanical properties are a priority [20,36,37].

Irrespective of the grade of the material, substrates are first soaked in water to hydrate them. Moisture is very important to fungal growth, and the duration of this stage varies from substrate to substrate as necessary [37]. Substrates such as rice hulls absorb very little moisture, making the duration of soaking less important than for inoculation media, such as wheat grains, which swell considerably and require soaking durations of at least 48 h [34]. Hydrated raw material is then homogenised to increase the growth surface area, which can be completed using low-energy mechanical processes, achievable using a kitchen blender, or grinding or milling depending on the requirements and manufacturing scale [37]. Macerated raw material is then sterilised to remove the microbial competition of existing bacteria and fungi already present in the material. This can be completed using high temperature conditions in an oven, but with the disadvantage of drying the substrate out, or a pressure cooker or autoclave, which keeps the substrate hydrated and is hence preferred. Chemicals, such as hydrogen peroxide (H_2O_2), can also be used to sterilise the substrate, but while less energy intensive than other sterilisation methods, are less effective, resulting in higher contamination rates [38].

Composite assembly itself is completed using a natural fungal growth process, which binds the lignocellulosic material into 3D geometries mirroring the mould shape that the substrate is packed into [9,10]. The lignocellulosic substrate is inoculated by introducing and evenly dispersing 10–32 wt% of any element of fungal biomass, such as spores in a liquid solution or hyphal or fruiting body tissue grown on a nutrient rich substrate, such as wheat grains, to the lignocellulosic material contained within the mould [9,39]. Spores have the advantage of being very easily and evenly dispersed throughout the substrate and provide many initial growth points, but require a nutrient-rich substrate, initially struggling to grow on low-grade materials. Grain- or sawdust-based inocula mitigate this problem by supplying a nutrient-rich substrate to support initial growth, which can then spread to lower-grade substrates but provide fewer initial growth points and are more difficult to evenly disperse [34].

Following inoculation, moulds can be stored under ambient conditions or in a temperature-controlled environment at ~25–27 °C for a growth period of days to months depending on the fungal species and substrate used and the degree of bonding desired [9,40]. Ambient conditions are obviously cheaper and more energy efficient to maintain but will result in slower growth than environments of elevated temperature. Following the growth period, the composite materials can be removed from the moulds and hot-pressed, oven or air dried to dehydrate the material and neutralise the fungus. This simultaneously ensures that it cannot grow further or spread while stiffening the composite material [39]. Hot-pressing and oven drying are favoured by industry as they are the fastest dehydration processes, with hot-pressing also consolidating and densifying the material thus resulting in higher mechanical properties. Fully processed mycelium composite materials are completely biodegradable and comprise ~95 wt% lignocellulosic material bound using ~5 wt% fungal mycelium for nutrient rich substrates (estimated based on an ergosterol concentration of ~870 ppm,

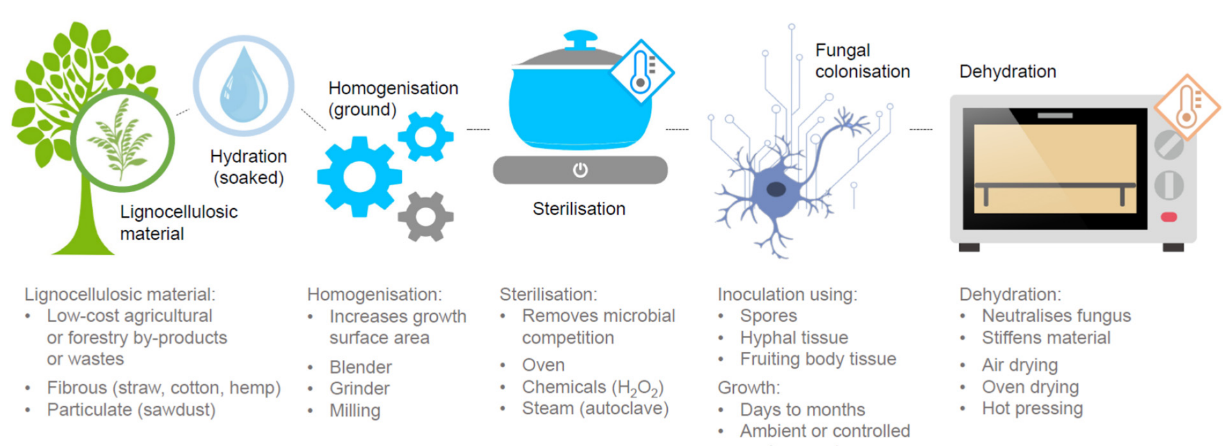

Fig. 2. Schematic of the manufacturing process of mycelium composites detailing the key stages, purpose and possible variations in the processes utilised during each stage.

corresponding to 50 mg of biomass for every 1 g wheat grains grown over 7 d) [41].

Foam-like physical and mechanical properties make mycelium composites suitable for non-structural construction applications including insulation materials and door cores. Mycelium composites are currently commercially available for these applications in the USA and Indonesia, although documentation relating to their physical and mechanical properties is not yet publicly available [42,43] (Fig. 3a). Mycelium-composite acoustic insulation foams are also a popular product that are commercially available in the EU and USA and are advertised as renewable materials exhibiting acoustic absorption properties competitive with other traditional commercial construction materials [42,44] (Fig. 3b). Textile applications are also attracting attention with significant advances being made in the development of very flexible mycelium-based polymer-like materials, with these materials currently sold via third party designers as finished products rather than as raw materials [45] (Fig. 3c). Impregnation of mycelium composites with a soy-based resin followed by curing can further extend their use to semi-structural applications, such as panelling, flooring, cabinetry and other furnishings, however the physical and mechanical properties of these materials are also not known [44,46] (Fig. 3d).

Despite the vast potential of these materials, which have been commercially available for over a decade, their adoption has been slow. Dell uses mycelium foams for packaging of business servers and IKEA has also expressed interest in adopting mycelium-based packaging [47,48]. Nevertheless, for the most part mycelium materials remain a predominantly underutilised niche product favoured by a select group of artists and designers, used to produce everything from furnishings such as chairs and lampshades to artistic structures, such as Philip Ross' "Mycotectural Alpha" tea house, to the 12 m high "Hy-Fi" organic compostable tower, comprising over 10,000 bricks, showcased by the New York Museum of Modern Art in 2014 [9,49–52]. This underutilisation could be the result of a patent monopoly on mycelium materials resulting in a lack of industrial commercial viability, a lack of trust in this new materials platform for applications beyond packaging or a lack of awareness among industry and the general public. Interest is however growing in mycelium materials with companies now active in the USA, Italy, Indonesia, the Netherlands and research spanning the USA, Italy, Belgium, the Netherlands, Australia, Austria and Switzerland [42–44,53–59].

With this growing research interest in the area of engineered mycelium composite materials, some recent reviews have addressed varying elements of this complex field. Most of these reviews engage the biological manufacturing processes associated with mycelium composite production [9,60–63] and the sustainability and life cycle of these materials [35,64,65]. However, this review focuses on investigating the composite engineering practises used to improve mycelium composite mechanical performance, discusses the material properties of these composites, factors influencing them and potential applications within the construction sector (Fig. 4). This review also aims to provide concise, quantifiable, tabulated data on the key material properties of these renewable composites as a single reference for the public, policy makers, industry and researchers to assess the viability of mycelium composites for tangible real-world applications.

3. Engineering of mycelium composite material properties

3.1. Influence of the mycelium binder on composite mechanical performance

The mycelium constituent of mycelium composites is often blamed for their limited mechanical performance [20,46]. However, recent studies investigating chitin-glucan extracts derived from mycelium have found the mycelium binder to be quite strong (tensile strengths up to 25 MPa [66] and for that of fruiting body extract up to 200 MPa [67]), suggesting that insufficient fungal growth density limiting mycelium binder quantity and mycelium binder to substrate filler interface are more likely to be responsible for limited mechanical performance. The species of fungus utilised as the mycelium to bind dispersed agricultural filler into mycelium composites affects growth density and the degree of interfacial bonding at the mycelium-substrate interface, which varies significantly by species and substrate [68], and does appear to affect the mechanical properties of the material. How well a fungal species grows on any given substrate is influenced by natural evolutionary factors. In nature, mesophilic (optimal growth at moderate temperatures) microflora are succeeded by thermophilic (optimal growth at high

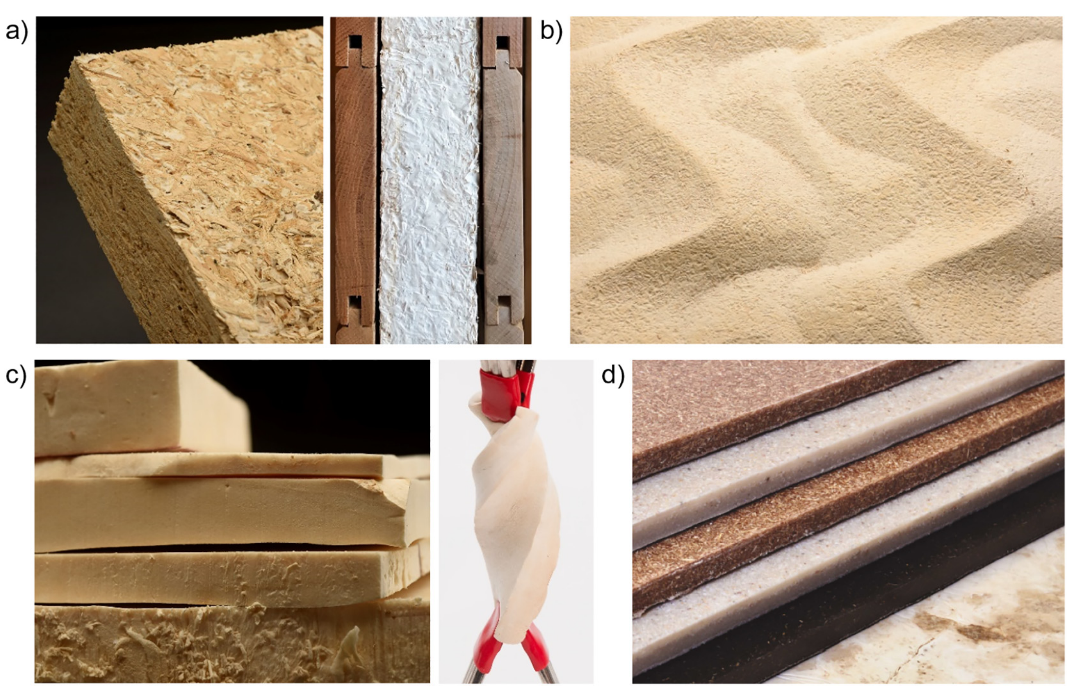

Fig. 3. Commercial mycelium composite construction materials as a) particleboard replacements for wall panelling and door cores, b) acoustic foams, c) flexible insulation foams and d) resin infused laminate flooring. Images courtesy of Ecovative Design LLC (Green Island, USA) and Mogu s.r.l (Inarzo, Italy).

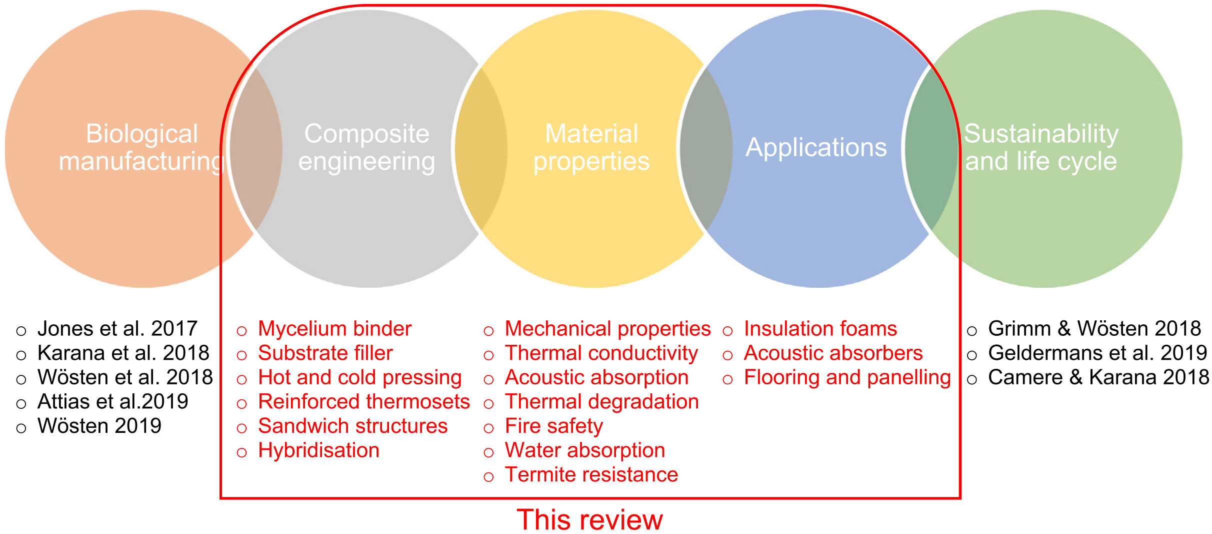

Fig. 4. Representation of the content and scope of this review in the field of engineered mycelium composite research with additional suggested reading material for interested readers, Jones et al. [9], Karana et al. [60], Camere and Karana [35], Wösten et al. [61], Attias et al. [62], Wösten [63], Grimm and Wösten [64], Geldermans et al. [65].

temperatures) microflora. Mesophiles accordingly thrive first with rising temperature, consuming the simpler carbon sources (sugars, amino acids, and organic acids) and leaving only polysaccharide constituents of biomass (cellulose and hemicelluloses) available for thermophiles. Many similar examples exist in nature, such as faster growing primary colonisers rapidly consuming available simple sugars and leaving only the more complex sugars available to the secondary and tertiary colonisers. This has led to natural affinities within these groups for these different carbon sources [69,70], which significantly affects how well a fungal species will grow on any given substrate. Since most mycelium composites are grown on lignocellulosic agricultural by-products and wastes, typically lacking optimal fungal nutrients, such as easily utilisable simple sugars (e.g. fructose, glucose and sucrose), white rot fungi, which degrade both cellulose and lignin (e.g. *Trametes*, *Ganoderma* and *Pleurotus* genera, phylum Basidiomycota), are typically used [10,13,31,34,37].

The mycelium binder network structure also affects the mechanical properties of mycelium composites. A good example is the mono-, di- and tri-mitic hyphal networks exhibited by basidiomycetes [71]. Hyphal networks of basidiomycetes can comprise up to three distinct hyphal types, generative, binding and skeletal, with key differences in cell wall thickness, internal structure and branching characteristics [9,72]. The number of different hyphal types present in a species is described using the mitic system. Monomitic species comprise only generative hyphae, dimitic species comprise two hyphal types (usually generative and skeletal) and trimitic species comprise of all three principle hyphal types [27]. Generative hyphae are thin walled, hollow and branched while skeletal hyphae are thick walled, often solid and sparsely branched or unbranched. Binding (ligative) hyphae are also thick walled, often solid and highly branched. It is generally accepted that complex hyphal systems (e.g. trimitic) are more advanced forms than less complex hyphal systems (e.g. monomitic) [71,73,74], with the wall thickness of the hyphal system and amount of water contained within their cells responsible for specific qualities of the biomass [75]. Although the tensile properties of fungal hyphae used in fermentation have been studied, with estimated hyphal ultimate tensile strengths of up to 24 MPa and elastic moduli of up to 140 MPa, the mechanical properties of wood-rot fungi hyphae are not well characterised [76–78]. Generative hyphae alone (monomitic hyphal systems), which are hollow and contain cytoplasm, are suggested to provide limited mechanical performance, with binding hyphae (dimitic and trimitic hyphal systems) responsible for material strength [79,80]. Although there is no literature confirming this, it is true that mycelium composites utilising trimitic species, such as *T. versicolor* or *multicolor* exhibit higher tensile (0.04 MPa) and flexural strengths (0.22 MPa) than monomitic species, such as *P. ostreatus* (0.01 MPa tensile strength, 0.06 MPa flexural strength) when grown on rapeseed straw [31]. *T. versicolor* also has a higher compressive strength than *P. ostreatus* when grown on hemp (0.26 MPa compared with 0.19 MPa) [38]. However, the fact that the presence of structural polymers, such as chitin and chitosan, is limited to the thin hyphal cell wall, which also contains polysaccharides (e.g. galactose, mannose and fucose), phosphate, proteins, lipids and mineral salts [28,66] makes the importance of the hyphal structure questionable, with mycelial biomass (binder) quantity likely to more greatly influence mechanical performance.

3.2. Influence of the substrate filler on composite mechanical performance

The physical and mechanical properties of as-grown mycelium composites are often dependent on the substrate, which acts as the dispersed substrate filler phase of the composite material. As-grown composites typically have a density ranging from 60 to 300 kg/m^3, with composites containing an agricultural by-product filler phase, such as bast fibers or straw, having lower densities (60–130 kg/m^3) than composites containing forestry by-product substrates, such as sawdust (87–300 kg/m^3) (Table 1). Only limited data is available on

Table 1
Density, tensile, compressive and flexural material properties of as-grown mycelium composites comprising fibrous and particulate dispersed agricultural filler substrates.

Loading	Substrate type	Substrate	$\rho_{envelope}$ (kg/m^3)	E MPa	$\sigma_{ultimate}$ MPa
Tension	Fibrous	Rapeseed straw[a]	115	3.0	0.025
	Particulate	Beech sawdust[a]	170	13.0	0.05
		Red oak sawdust[b]	300	1.30	0.18
Compression	Fibrous	Flax hurd[c]	99	0.73	–
		Hemp hurd[c]	94	0.64	–
		Wheat straw[d]	192	–	0.17
	Particulate	Pine shavings[c]	87	0.14	–
		Red oak sawdust[b]	300	1.0	0.49
		White oak sawdust[d]	552	–	1.1
Flexure	Fibrous	Cotton fibers[a]	130	1.0	0.05
		Rapeseed straw[a]	115	1.5	0.14
	Particulate	Beech sawdust[a]	170	9.0	0.29

[a] Data from Appels et al. [31].
[b] Data from Travaglini et al. [20].
[c] Data from Elsacker et al. [37].
[d] Data from Ghazvinian et al. [85].

the mechanical properties of mycelium composites for the various groups of substrates.

Tensile properties are among the best characterised material properties of mycelium composites. Reported tensile properties vary significantly between studies for sawdust substrates (0.05–0.18 MPa) but sawdust does appear to be associated with higher tensile strengths than straw substrates (0.01–0.04 MPa) (Table 1). However, the tensile properties of as-grown sawdust-based mycelium composites do not correlate with the mechanical properties of the substrates themselves. Clear, straight grained Beech wood sections have a similar or higher tensile strength perpendicular to the grain (5–7 MPa) than red oak (5.5 MPa) [81,82], while as-grown composites using a beech sawdust substrate have much lower tensile strength (0.05 MPa) than composites with a red oak sawdust substrate filler (0.18 MPa). This indicates that the tensile properties of as-grown mycelium composites are more heavily influenced by failure of the mycelium binder than the dispersed substrate filler and that substrates must be nutrient rich, rather than strong, to establish a dense mycelium network and maximise mycelium composite tensile properties. Some lower-grade substrate materials, such as agricultural by-products and wastes, which are attractive due to their low cost, typically lack optimal fungal nutrients including easily utilisable simple sugars (e.g. fructose, glucose, sucrose) and instead contain more complex carbon sources (e.g. cellulose and lignin) [83]. While white rot fungi are suitable for these lignocellulosic substrates, some agricultural by-products, like rice hulls, also contain large quantities of minerals, such as silica, which limit fungal growth [41]. Reduced fungal growth on these less easily utilised substrates compromises interfacial bonding between hyphae and organic matter and adversely affects the tensile strength of the mycelium binder [20,41,84].

Unfortunately, inconsistent and limited data is available concerning the compressive properties of mycelium composites. Elsacker et al. [37] found that the compressive moduli of as-grown composites utilising fibrous hemp and flax hurd substrates were higher than those of particulate pine shavings (0.64 and 0.73 MPa compared to 0.14 MPa, respectively), however their study only tested to 70–80% strain and subsequently did not assess compressive strength. Conversely, Ghazvinian et al. [85] assessed the compressive strength of mycelium composites grown on a white oak sawdust and a wheat straw substrate, finding that the sawdust particulate substrate had a much higher compressive strength than the fibrous straw (1.1 MPa compared to 0.17 MPa, respectively), but did not assess stiffness (Table 1). Only Travaglini et al. [20] assessed both compressive modulus (1 MPa) and strength (0.49 MPa) of mycelium composites with a red oak sawdust substrate. Despite significant gaps in the characterisation of mycelium composites under compressive loading conditions, it seems likely that particulate substrates, such as sawdust, provide higher compressive properties to the composite than fibrous substrates such as straw. The compressive properties of porous materials are strongly correlated with their porosity and pore size, with increased porosity associated with reduced mechanical performance [32,86]. This suggests that the compressive performance of as-grown composites would depend on the compressive properties and porosity of the substrate filler, the composite itself and the degree to which the fungus digests the filler, increasing its porosity in the process [33]. However, the compressive properties of as-grown composites have been found to be largely independent of the particle size of the substrate filler phase [87].

Particle geometry also had no significant effect on the flexural strength of mycelium composites, which when subjected to bending experience a maximum tensile stress at one surface, to zero at the midplane, to a maximum compressive stress at the opposite surface [88]. Although fibrous geometries should improve the tensile properties of the surfaces if aligned in the loading direction, and hence the flexural properties of the composite overall [89], the significant fungal growth on air exposed surfaces likely results in enzymatic fiber degradation and damage, compromising the beneficial effects of the fibers present [90]. Air transmission is critical for fungal growth with mycelial density highest at the air exposed surfaces and lowest in the core, where depending on the porosity of the substrate filler there could be limited or even no growth unless the filler is artificially aerated [27,91]. The lack of improvement in the flexural properties of mycelium composites incorporating fibrous surfaces was supported by the poor flexural properties of cotton fiber-based composites (1 MPa and 0.05 MPa, respectively), although fibrous straw-based composites did exhibit better flexural stiffness (1–3 MPa) and strength (0.06–0.22 MPa) (Table 1). Conversely, a particulate Beech sawdust substrate resulted in much higher flexural modulus (9 MPa) and strength (0.29 MPa), which was most likely the result of its nutrient composition promoting the formation of a dense, continuous mycelium binder on the air exposed surface of the composite. The importance of the substrate nutrient profile to composite flexural properties is supported by results obtained by Tudryn et al. [92], who found that increased nutrition at homogenization increased specific flexural stress and specific flexural modulus, due to the presence of a larger, more continuous mycelium binder.

In general, the value of any given substrate in reinforcing the composite appears to be more heavily governed by the nutrient profile of the substrate with more nutritious substrates promoting more fungal growth and bonding, since failure always occurs in the mycelium binder rather than the substrate filler irrespective of loading condition. This unfortunately makes cheap, low-grade agricultural and forestry residues often only suitable for the manufacture of foam-like mycelium composites, unless further processing techniques, such as hot or cold pressing, resin infusion or hybridisation are utilised to improve mechanical performance [41].

3.3. Hot and cold pressing to improve mycelium composite mechanical properties

The mechanical properties of mycelium composites can be significantly improved using physical processing, such as cold or hot pressing. This is expected since pressing consolidates composite materials, reduces the porosity of the material and increases the material density in general [93]. Pressing also helps to reorientate fibers horizontally in the plane of the panel [94] and panel thickness reduction during pressing results in considerable and intimate fiber contact between the walls of the fibers at points of overlap [95]. In mycelium composites produced using *P. ostreatus* grown on rapeseed straw, cold pressing was associated with a significant improvement in tensile strength (0.01 MPa to 0.03 MPa) and a higher elastic modulus (2 MPa to 9 MPa) [31]. It also significantly improved the flexural properties of the composites with higher flexural strengths (0.06 MPa to 0.21 MPa) and moduli (1 MPa to 15 MPa) achieved post cold pressing [31]. Even greater improvements in mechanical performance could be achieved through hot pressing. The main mechanisms associated with hot pressing are the phase change (evaporation) of water, compaction and stress relaxation of the material via conduction and convection and mass transfer occurring as a result of gaseous and bound water diffusion and hydrodynamic flow of gaseous and liquid water [95]. This occurs via diffusion of steam through the network or voids in fibers, diffusion of water through cellular walls or as water or steam flow through cell membranes and voids [96]. Temperature, gas pressure and moisture content all influence the heat and mass transfer through the thickness, impacting plasticization and compaction of the material [95]. Tensile properties of hot-pressed *T. multicolor* and *P. ostreatus* composites grown on rapeseed straw were significantly higher than as-grown samples, with strength increases of 0.04 MPa to 0.15 MPa and 0.01 to 0.24 MPa, respectively, and elastic moduli increases of 4 MPa to 59 MPa and 2 MPa to 97 MPa, respectively [31]. Hot pressing also improved the flexural strength of *T. multicolor* and *P. ostreatus* composites grown on rapeseed straw (0.22 MPa to 0.86 MPa and 0.06–0.87 MPa, respectively) and the flexural moduli of the composites (3 MPa to 80 MPa and 1 MPa to 72 MPa, respectively) [31]. Both cold and hot pressing were associated with significant reductions in the strain to failure of the samples, resulting from the reduced moisture content of the composites following pressing, which would otherwise act as a plasticiser [97]. Cold pressing of *P. ostreatus* grown on rapeseed straw reduced their strain to failure (2.8% to 0.8%), while hot pressing of *P. ostreatus* and *T. multicolor* grown on rapeseed straw was associated with lower strain to failure (2.8% to 0.7% and 4.7% to 0.9%, respectively) [31].

3.4. Mycelium composite reinforced thermosets and sandwich structures

Mycelium composites are being increasingly used as low-density cores bonded between two thin laminate facings called skins in sandwich structures [23,46,98]. Skins can be any sheet material, from metals such as aluminium [98], to natural materials such as woven jute, flax or cellulose [23]. These skins provide resistance against in-plane and lateral bending loads, while the mycelium core holds the skins in place and resists shear loads [99–101]. The improvement in mechanical performance that a sandwich structure provides is subsequently dependent on the loading conditions. Several recent studies have examined the use of mycelium composites in sandwich structures but any significant improvement in mechanical performance has yet to be reported, making the value of mycelium sandwich composites debatable. Wong et al. [98] recently reported unsurprisingly that a sandwich structure comprising a mycelium composite sandwiched between aluminium alloy laminates had no better compressive properties than a normal mycelium composite and while skins provide varying degrees of improvement to the flexural strength of sandwich structures with a mycelium composite core, similar results can be achieved using simpler methods. For example, mycelium composite sandwich structures comprising jute, flax or cellulose textile reinforcement skins have effective flexural moduli of 4.6–6.5 MPa [23], with similar performance achievable by simply varying the substrate of the mycelium composite itself (flexural moduli of 1–9 MPa) or hot-pressing (flexural moduli of 34–80 MPa) [31].

The most significant improvement in the mechanical performance of sandwich structures with mycelium composite core and a woven jute, flax or cellulose skin was achieved by resin infusion. This is also hardly surprising or even novel since the use of a mycelium composite reinforced resin effectively replaces the mycelium binder with a stronger resin one. The difference between a resin-infused mycelium composite and a natural composite comprising resin and agricultural residue or fibers is then unclear as is the sustainability of such a composite, which lacks a natural biological manufacturing process. Jiang et al. [46] reported that soy-based resin infused over 30–120 s saturates the entire material and is responsible for an improvement in core and skin shear yield and ultimate stress and sandwich flexural strength. Core shear yield stress and ultimate strength were highest for resin-infused samples reinforced with flax skins (up to 128.9 yield and 135.3 kPa ultimate stress) [46]. This was due to the increased mycelial growth on these skins, since the nutrient profile of flax stimulates more fungal growth than jute or cellulose, facilitating greater branching networks and interfacial bonding. The resin infusion unsurprisingly provided a significant improvement compared to flax sandwich composites lacking resin (core shear yield and ultimate stresses of up to 29.5 kPa and 38.7 kPa, respectively) [23]. The most common failure mode of the sandwich structures was tensile failure of the core material (mycelium-bound agricultural waste), indicating that this was still the weakest part of the structure. Effective flexural strengths of up to 30 MPa for resin-infused flax reinforced sandwich structures were achieved, which are significantly higher than flax-reinforced sandwich structures lacking resin (up to 6 MPa) [23] and low-density polyethylene (LDPE) (14 MPa) but lower than acrylonitrile butadiene styrene (ABS) (75 MPa) [102]. The sandwich structures (410 kg/m^3) also had lower densities than LDPE (920 kg/m^3) and ABS (1100 kg/m^3) and were suggested as potential replacements for LDPE and ABS interior panels in automotive and sports products.

3.5. Hybridisation of mycelium composites to improve mechanical performance

The mechanical properties of mycelium composites, comprising a network of fungal mycelium grown through a substrate, can be improved through hybridisation with small quantities of synthetic rubbers, such as styrene-butadiene rubber, or natural reinforcements, such as cellulose nanofibrils. While these improvements are arguably predictable when hybridising a weak mycelium composite with stronger synthetic or natural polymers, the small volume fractions required to do so, and the thresholds associated with mechanical property improvement are interesting. Styrene-butadiene rubber negligibly affects fungal growth performance in quantities up to 5 vol% with only a slight delay in germination and no effect on the growth rate [84]. Larger volumes of the latex hinder growth (8 vol%) or kill the fungus (10 vol%) since the latex reduces the void volume within the composite, hindering the oxygen transmission and absorption required for fungal growth [33,84]. Mycelium composites produced using cotton seed hulls and *P. ostreatus* had a compressive strength of 177 kPa, which could be almost doubled with the addition of 5 vol% styrene-butadiene rubber (343 kPa) [84]. This is due to the void volume reduction and volume density increase (181 kg/m^3 to 225 kg/m^3) associated with the inclusion of the latex [84]. Even smaller quantities of nanocellulose can be used to improve mechanical performance with increases in flexural strength (1.5 MPa to 3.5 MPa) and modulus (220 MPa to 575 MPa) of hybrid materials produced by cold and hot pressing wood particles with mycelium growing on them hybridised with 2.5 wt% nanocellulose [103]. Notably, further increases in nanocellulose content did not provide any significant improvement in mechanical performance suggesting a low threshold nanocellulose density required for improvement of adhesion of particles and subsequent flexural properties [104,105]. These improvements in mechanical performance at low nanocellulose concentrations could make hybridisation using nanocellulose a viable method for improving the mechanical performance of mycelium composites. However, in some cases, such as hybridisation using latex, the small improvement in mechanical performance attained post hybridisation may well be offset by the additional costs, processing and reduced environmental sustainability associated with a latex-mycelium composite material.

3.6. Thermal conductivity properties of mycelium composites for insulation applications

Mycelium composites containing high-performance natural insulators such as straw and hemp fibers bound using mycelial growth have both low densities (57–99 kg/m^3) and thermal conductivities (0.04–0.08 W/m·K) (Fig. 5). This makes them excellent insulation materials, able to compete with conventional commercial thermal insulation products, such as glass wool (57 kg/m^3, 0.04 W/m·K) and extruded polystyrene insulation (XPS, 34 kg/m^3, 0.03 W/m·K) [106] in addition to other natural insulators including sheep wool (18 kg/m^3, 0.05 W/m·K) and kenaf (105 kg/m^3, 0.04 W/m·K) [107].

Lower thermal conductivities are associated with better insulation materials and are primarily influenced by material density and to a lesser extent moisture content [108–110]. For example, a 67% increase in density will result in a 54% increase in thermal conductivity in hemp concretes (a bio-composite material comprising hemp shive and lime), while a 90% increase in relative humidity (completely dry to 90% RH) will only result in a thermal conductivity rise of 15–20% [108]. The strong correlation between material density and thermal conductivity is the result of the presence of large quantities of dry air, which has a very low thermal conductivity (26.2×10^{-3} W/m·K at 0.1 MPa, 300 K) [111], present in low density materials. These large quantities of air mean that low density materials are often excellent thermal insulators.

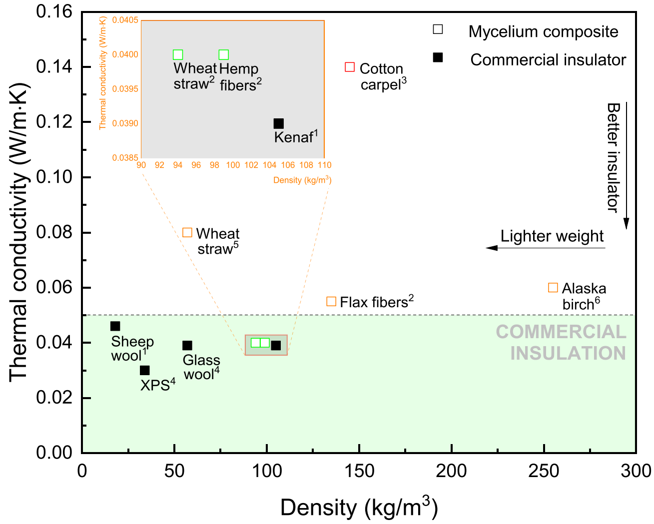

Fig. 5. Density (kg/m^3) and thermal conductivity (W/m·K) of mycelium composites produced using various substrates (coloured square markers, colours: green = low thermal conductivity, orange = medium thermal conductivity, red = high thermal conductivity) and commercial insulation materials, such as glass wool, sheep wool, XPS foam and kenaf (black solid square markers). Data from [1]Asdrubali et al. [107], [2]Elsacker et al. [37], [3]Holt et al. [10], [4]Papadopoulos [106], [5]Xing et al. [36] and [6]Yang et al. [117]. Density and thermal conductivity values are averages based on the available data sets. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Straw and hemp are well-established natural thermal insulation materials, which derive their useful insulation properties from their porous structure and the low bulk density of the bundled fibers, leading to trapping of a large amount of air between the fibers in the insulation [112,113]. Their thermal insulation properties vary primarily based on the density of the pack, moisture content and fiber type [114]. Mycelium composites utilising a wheat straw filler have reported thermal conductivities of 0.04 W/m·K [37] and 0.08 W/m·K [36], respectively, although the former value seems questionable given that it is associated with a higher density composite than the latter (94 kg/m^3 compared to 57 kg/m^3) and is significantly lower than the conductivity of straw bales themselves (0.07–0.08 W/m·K) [115]. Hemp fiber-based mycelium composites were also reported to have thermal conductivities (0.04 W/m·K) [37] significantly lower than hemp concretes (0.1 W/m·K) [108]. Even mycelium composites produced using substrates exhibiting poorer insulation properties, such as those incorporating a cotton carpel substrate (0.10–0.18 W/m·K) [10] have thermal conductivity values comparable with gypsum (0.17 W/m·K), high density hardboard (0.15 W/m·K), plywood (0.12 W/m·K), and both hardwoods (0.16 W/m·K) and softwoods (0.12 W/m·K) [116]. This makes mycelium composites a viable low-cost and environmentally sustainable alternative to conventional commercial building insulation materials.

3.7. Acoustic properties of mycelium and its composites as noise barriers

Mycelium itself is an excellent acoustic absorber, exhibiting strong inherent low frequency absorption (<1500 Hz) and outperforming cork and commercial ceiling tiles in road noise attenuation [118]. This non-typical property means that mycelium foam can be used in conjunction with other materials to improve their low frequency absorption properties. Alternatively, mycelium composite comprising mycelium-bound agricultural residue can also provide broader range acoustic absorption with 70–75% absorption or better achievable for perceived road noise [11]. A-weighted decibels express the relative loudness of sounds in air as perceived by the human ear, with the magnitude of low frequency sounds reduced to correlate with the lessened sensitivity of human ears at low frequencies (<1000 Hz), while higher frequency sounds are left uncorrected [119]. This allows interpretation of the perceived loudness of domestic noises, such as dogs barking (500–1500 Hz), human speech (85–255 Hz) and street noise (700–1300 Hz) to humans [120–123].

Acoustic absorbers are typically fibrous, porous or reactive resonators with examples including nonwovens, fibrous glass, mineral wools, felt and foams [124,125]. Absorbers convert the mechanical motion of air molecules travelling in sound waves into low-grade heat, which prevents sound accumulation in enclosed spaces and reduces reflected noise strength [124]. All mycelium composites tested were associated with lower perceptual road noise (45.5–60 dBa) than traditional reference absorbers, such as commercial ceiling tiles (61 dBA), urethane foam board (64 dBA) and plywood (65 dBA) (Fig. 6a, b). The best individual substrate fillers for acoustic absorption were rice straw (52 dBa), hemp pith (53 dBA), flax shive (53.5 dba), sorghum fiber (54 dBa) and switchgrass (55 dBa) (Fig. 6a). However, even better acoustic absorption could be achieved through mixtures of fillers (50–50 wt%) with the best combinations being rice straw-sorghum fiber (45.5 dBa), rice straw-cotton bur fiber (47 dBa) and sorghum fiber-switchgrass (47 dBa) (Fig. 6b).

The excellent acoustic absorption properties of mycelium composites can be attributed to their porous, fibrous nature. Impedance and propagation constants used to describe the acoustic properties of materials are greatly influenced by the air flow resistance of a material, with higher airflow resistance associated with greater acoustic absorption [126]. The fibers in mycelium composites act as frictional elements, resisting acoustic wave motion and decreasing its amplitude as the sound waves attempt to move through the tortuous passages of the material and are converted to heat in the process [127]. Thin fibers provide better acoustic absorption since they can move more easily and the greater number of fibers per unit volume results in more tortuous paths and greater air flow resistance [128,129]. Surface pore concentration and geometry are also important with porosity necessary for sound waves to enter the material and tortuosity required for efficient damping [125]. Porosity and airflow resistance affect the height and width of sound wave peaks, while tortuosity influences the high frequency acoustic properties of porous materials [125]. Less dense, more open structures absorb low frequency sound in nonwoven fibrous materials (500 Hz), while denser structures are better for frequencies higher than 2000 Hz [128]. Compression of a material causes a reduction in acoustic absorption, resulting primarily from the reduction in thickness [130], and as such mycelium composites being utilised as acoustic absorbers should not be hot or cold pressed.

3.8. Thermal degradation and fire safety properties of mycelium and its composites

Mycelium itself has no notable or useful fire-retardant properties, typically exhibiting a three-stage thermal degradation process, with degradation and fire reaction properties typical for cellulosic and other biologically derived materials [13,131,132]. Initially, free and chemically bonded water evaporates between 25 and 200 °C (~5 wt%) [91]. This is followed by a much larger mass loss between 200 and 375 °C, with onset of decomposition at ~280–290 °C [13,34,91]. This larger mass loss results from the degradation of organic constituents, such as proteins and polysaccharides (~70 wt%) and is associated with water vapour release [91]. The release of water vapour during combustion is the only true fire-retardant property of mycelium, making mycelium thermally no better as a binder than any other natural polymer [91]. Although hyphal constituents, such as chitosan and hydrophobins (cysteine-rich proteins that form a hydrophobic coating), have been found to improve fire retardancy in fabrics, they do not occur in sufficient quantities to provide fire retardancy properties in mycelium [91,133–136]. Hydrophobins in particular have been reported to promote char formation by favouring dehydration rather than depolymerisation of polysaccharides [136], but genetically modified *Schizophyllum commune* mycelial biomass lacking its hydrophobin gene has actually been

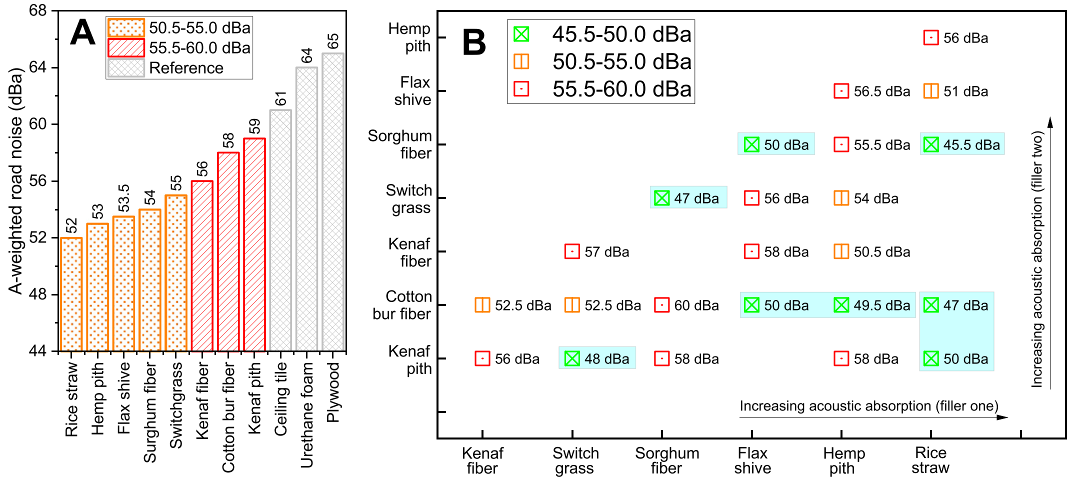

Fig. 6. A-weighted perceptual road noise for mycelium composites comprising a) individual substrates compared to traditional acoustic absorbers and b) 50–50 wt% mixtures of selected substrate fillers. Colours: green cross: 45.5–50.0 dBa, orange line: 50.5–55.0 dBa, red dot: 55.5–60.0 dBa, grey: traditional reference absorbers. Data is based on an integrated A-weighted response with typical road noise excitation (1000 Hz) rounded to the nearest 0.5 dBa from Pelletier et al. [11]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reported to have higher char yields (32 wt% average) than wild type *S. commune* biomass (27 wt% average) [30]. Approximately 20–30 wt% carbonaceous char is typically formed at 450–600 °C for mycelial biomass pyrolyzed in a nitrogen atmosphere [13,30,91].

Although mycelium itself does not have significant fire-retardant properties, mycelium composites incorporating substrates or fillers that are rich in natural phenolic polymers, such as lignin, and naturally occurring or synthetically produced silica (SiO_2) can exhibit significantly improved thermal degradation, fire reaction and safety properties [34]. This is not entirely surprising since the substrate filler phases constitute the bulk of the material anyway and if inflammable or difficult to burn will lend their properties to the composite. Rice hulls contain 25–30 wt% lignin [137] and 15–20 wt% silica, which is biosynthesized through the polymerization of silicic acid and distributed in the hulls as hydrated grains [138]. Glass fines comprise primarily of silica (SiO_2), but can contain up to 30 wt% organic surface matter, which is sufficient for mycelial growth to bind to as opposed to uncontaminated glass, which mycelium cannot grow on [34]. Both rice hulls and glass fines are considered waste materials and are available in large quantities globally at low cost [8,139–141].

Mycelium composites containing large quantities of rice hulls (75 wt %) have lower average and peak heat release rates (107 kW/m^2 and 185 kW/m^2, respectively) compared to synthetic foams, such as extruded polystyrene insulation foam (XPS, 114 kW/m^2 and 503 kW/m^2, respectively) and engineered woods, such as particleboard (134 kW/m^2 and 200 kW/m^2, respectively) (Table 2). Since both extruded polystyrene and engineered wood resins, such as resorcinol- and polyvinyl acetate-based resins, are derived from crude oil this is hardly a surprise and the logic of the widespread use of synthetic materials that have not been treated to improve their thermal stability in fire prone applications, such as construction, is questionable. Heat released from burning material provides additional thermal energy to fires and strongly influences their behaviour [142] and reaction properties including surface flame spread, smoke generation and carbon monoxide emission [143,144]. Heat release rate (HRR) is subsequently considered the most important fire reaction property due to its role in fire growth and spread [145,146], with the average value (RHR_{180}) indicating full-scale fire performance [147] and the peak value (pHRR) suggesting maximum temperature and flame spread rate [142].

The lower heat release rates associated with rice hull-based mycelium composites are attributable to the higher charring rice hulls (~20 wt% carbonaceous char residue and ~20 wt% embedded silica) [131,148], rather than the mycelium, which only represents ~5 wt% of the composite and yields less char (~20–30 wt%) [41,91]. Char is derived from organic constituents of rice hulls, especially aromatic compounds such as lignin, which decomposes into aromatic fragments that form char [149]. Char formation and oxidation on air exposed surfaces increases flame retardancy, acting as a thermal insulation barrier due to its low thermal conductivity [142] and reducing smoke by impeding fiber fragment release and preventing oxidation [150,151].

Addition of glass fines within the substrate of the composite further improves the fire reaction and safety properties of mycelium composites which is logical, since it significantly increases the silica (inflammable) content of the material. Mycelium composites incorporating 50 wt%

Table 2
Summary of cone calorimetry performance and fire safety parameters.
Data from Jones et al. [34].

Type	Sample	Time		Heat release rate		Gas release		
		Ignition, t_{ig} (s)	Flashover, t_{fo} (s)	Average, RHR_{180} (kW/m^2)	Peak, pHRR (kW/m^2)	Smoke, TSR (m^2/m^2)	CO, COP_{180} (g)	CO_2, CO_2P_{180} (g)
Synthetic	ClimaFoam® extruded polystyrene insulation foam	9	61	114	503	1184	0.48	15.2
	STRUCTAflor® particleboard	26	173	134	200	64	0.47	30.0
Mycelium composite[a]	75 wt% wheat grains	12	94	107	185	70	0.33	23.8
	75 wt% rice hulls	7	75	85	133	40	0.02	14.6
	25 wt% wheat grains +50 wt% glass fines	12	370	42	79	5	0.39	10.2
	25 wt% rice hulls +50 wt% glass fines	7	311	33	85	0.9	0.91	6.3

t_{ig} = time to ignition, RHR_{180} = average heat release rate from ignition to 180 s after ignition, pHRR = peak heat release rate, t_{fo} = estimated time to flashover in room fire test [154], TSR = total smoke release, COP_{180} = carbon monoxide produced from ignition to 180 s after ignition, CO_2P_{180} = carbon dioxide produced from ignition to 180 s after ignition.
[a] Inoculated using 25 wt% wheat grain inoculum.

glass fines have much longer times to flashover (311–370 s) than synthetic materials, such as extruded polystyrene insulation foam (XPS) (61 s) and particleboard (173 s) (Table 2). Flashover is the near-simultaneous ignition of all exposed materials in an enclosed area and is a common and very dangerous occurrence in residential and building fires [152]. Fires that reach flashover are approximately ten times more dangerous than fires that do not [152,153]. Composites incorporating large quantities of glass fines (50 wt%) also have very low average (33–42 kW/m^2) and peak (79–85 kW/m^2) heat release rates compared to synthetic construction materials, such as XPS (114 kW/m^2 average and 503 kW/m^2 peak) and particle board (134 kW/m^2 average and 200 kW/m^2 peak) (Table 2).

However, despite the dangers associated with heat release and flashover, most fire-related fatalities are caused by toxic gases rather than burns, generalised trauma or other causes [142,154]. Carbon monoxide (CO) causes incapacitation and death at very low concentrations (e.g. 1500 ppm will cause death within an hour) and is considered the greatest individual hazard [155]. In contrast, carbon dioxide (CO_2) concentration must be >60 times higher (100,000 ppm) to cause death over the same period [142]. Rice hull-based mycelium composites have much lower CO emission (0.02 g) than particleboard (0.47 g) and XPS (0.48 g), in addition to lower CO_2 emission (14.6 g compared to 15.2 g for XPS and 30.0 g for particleboard) (Table 2). Wheat grain- and rice hull-based mycelium composites incorporating 50 wt% glass fines also emit much less smoke (0.9–5 m^2/m^2) than traditional construction materials, such as particleboard (64 m^2/m^2) and XPS (1184 m^2/m^2) (Table 2). Short-term exposure to smoke consisting of small fragments of fiber and ultra-fine carbon particles is not considered a serious health hazard to humans but is an important safety concern because dense smoke can reduce visibility, cause disorientation and hinder firefighting efforts [142].

3.9. Water absorption properties of mycelium composites

One of the biggest issues limiting the use of mycelium composites in materials science applications is their tendency to absorb large amounts of water quickly. Mycelium composites are typically hydroscopic, increasing in weight by ~40–580 wt% when in contact with water for 48–192 h [10,21,31,37,103]. The strong water absorption affinity of mycelium composites is the result of their typically cellulosic filler constituents, which contain numerous accessible hydroxyl groups [156], and the hydrophilic porous mycelium binder and biologically derived filler phases, which promote wicking [157–159]. Air dried mycelium composites incorporating a fibrous substrate of rapeseed straw or cotton bur fiber take up ~530–550 wt% moisture within 48 h when in contact with water (Fig. 7a). Although such a massive water uptake may seem a major problem some construction applications for mycelium composites, such as acoustic or thermal insulation, are fortunately for internal or dry locations that are not exposed to the weather, mitigating this otherwise significant problem. The most rapid weight increase occurs within the first 3 h, with an increase of ~220 wt% for both rapeseed straw- and cotton bur fiber-based composites (Fig. 7b). Water uptake then continues at a reduced rate for up to 48 h, before slowing and then stopping as the material reaches saturation (~580 wt%) (Fig. 7a). Rapeseed straw contains large quantities of cellulose (48.5 wt%) and pentosans (17 wt%) [160], while cotton bur fibers predominantly comprise cellulose (98 wt% with <0.5 wt% pentosan) [161]. Pentosans are water soluble polymers composed of pentoses and are known to increase the amount of water absorbed by bread, while the hydroxyl groups in cellulose attract water molecules [156,162]. In contrast, mycelium composites comprising a particulate substrate, such as beech sawdust, are much less susceptible to water uptake with a weight increase of 23 wt% over 3 h contact with water, which slowly increases to 43 wt% over 192 h (Fig. 7a). Beech sawdust contains 26 wt% hydrophobic lignin in addition to its 48 wt% cellulose [163], which in conjunction with its higher material density and the smaller void content of the fine particulate substrate filler, is likely to account for its reduced water uptake.

Hot or cold pressed mycelium composites also experience less than half the water uptake of air-dried composites (~250 wt% compared to ~580 wt%) (Fig. 7a). This is most likely because pressed materials have smaller void volumes, which impedes capillary action and hence water uptake [93]. Cold pressed mycelium composites are slightly less absorbent (214 wt% after 48 h, 238 wt% after 192 h) than hot pressed composites (247 wt% after 48 h, 252 wt% after 192 h), achieving saturation faster than the drier hot-pressed composites since they are initially more hydrated. Heat treatment of lignocellulosic polysaccharide components, such as the depolymerisation of hemicelluloses at temperatures above 160 °C, can reduce water absorption due to the reduced number of free hydroxyl groups present [164,165]. However, since hot pressing primarily heat treats the mycelium-rich surfaces it is likely that any improvement in water absorption properties based on depolymerisation of hemicelluloses would only be realised through more uniform temperature application affecting the lignocellulosic core, such as oven drying. In addition to using particulate substrate fillers and pressing, many bio-based coatings, such as polyfurfuryl

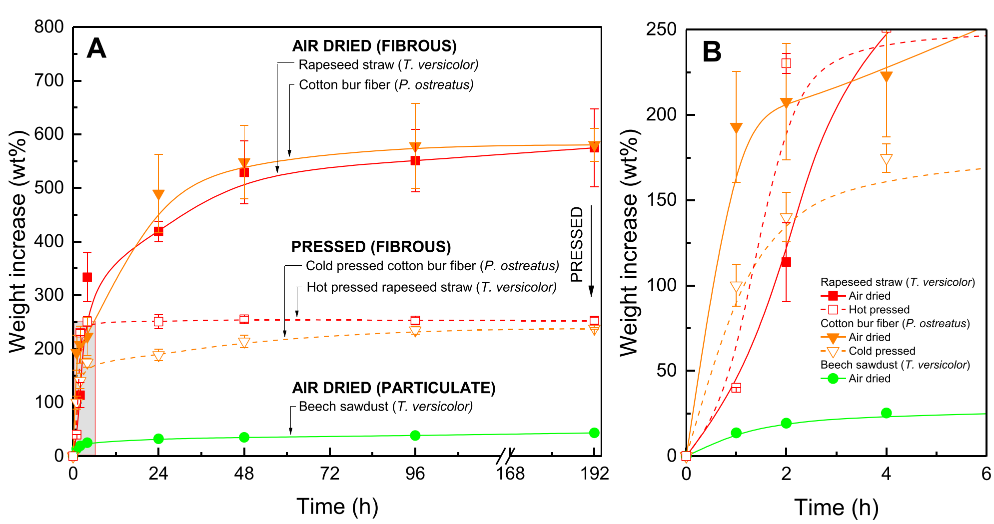

Fig. 7. Moisture uptake (wt%) of air dried (solid lines) and hot and cold pressed (dotted lines) fibrous (*P. ostreatus* on cotton bur, orange, *T. versicolor* on rapeseed straw, red) and particulate (*T. versicolor* on beech sawdust, green) mycelium composite materials resulting from continuous contact with a water surface over (a) 192 h with (b) the most rapid absorption period (0–6 h) magnified. Data from Appels et al. [31]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

alcohol resin (PFA), have also shown promise in reducing water absorption in natural fiber composites [166] and could be applied to mycelium composites to improve their water resistance.

3.10. Termite resistance of mycelium composites

Termites are a significant threat to residential and commercial buildings in many countries around the world with annual global estimates of structural damage to buildings from termites running into the billions of dollars [167]. They are most prolific in Africa, Asia, South America and Australia but are also prominent in North America where they cause in excess of $US 100 million of damage each year to houses and businesses in New Orleans alone [168]. Mycelium composites have no termite resistant properties of their own, comprising completely biological and predominantly lignocellulosic material. However, termite resistance of mycelium composites can be improved through substrate selection and application of natural or commercial termiticides [169]. Hemp-based mycelium composites have high termite-resistance, exhibiting high termite mortality rates (directly related to efficacy or repellence by termite treatments) and low mass losses resulting from termite infestation over 4 weeks (16–53 wt%). Kenaf-based composites exhibit moderate to complete termite mortality but are associated with the highest mass losses of any untreated mycelium composite (43–62 wt%). Corn-based composites have low termite resistance with slight to moderate termite mortality and 42–43 wt% mass loss. The most effective natural termiticides are guayule resin (flavonoid, cinnamic, terpenoids, and p-anisic acid bioactive compounds) [170] and vetiver oil (α- and β-vetivone bioactive compounds) [171]. A single coating of these oils provides complete termite mortality and are associated with mass losses of 18–28 wt% and 16–27 wt%, respectively, for treated mycelium composites. This mass loss is significantly less than for untreated composites (42–62 wt%) and an untreated southern yellow pine (*Pinus taeda*) reference sample (80 wt%). Commercial borax termiticide provides less termite protection than the natural oils with 28–40 wt% mass loss resulting from termite infestation. The fungal species *Daedaleopsis confragosa*, *Ganoderma resinaceum* and *Trametes versicolor* have no significantly different effects on termite repellence or mass loss for mycelium composites. Other degradation parameters of mycelium composites, such as mould and weathering resistance remain undocumented.

4. Critical assessment of mycelium composites

Mycelium composites comprising low-weight substrates, such as rice hulls (59 kg/m^3), are competitive in terms of weight with common synthetic insulation foams, such as polystyrene (PS, 11–50 kg/m^3), polyurethane (PU, 30–100 kg/m^3) and phenolic formaldehyde resin foams (PF, 35–120 kg/m^3) (Table 3). They are also much lighter than all typical

Table 3
Comparison of the cost, physical, mechanical, fire, thermal conductivity, acoustic absorption, moisture uptake, termite resistance, manufacturing and end of life properties of mycelium composites and typical synthetic foams (polystyrene (PS), polyurethane (PU) and phenolic formaldehyde resin (PF)) and wood products (plywood (PW), softwood (SW), hardwood (HW)) used in construction.
Data from Holt et al. [10], Pelletier et al. [11], Travaglini et al. [20], Appels et al. [31], Jones et al. [34], Elsacker et al. [37], Jones et al. [41], Ghazvinian et al. [85], Zabihzadeh [156], Bajwa et al. [169], ASTM International [172], NPCS Board of Consultants & Engineers [173], Ashby [174], Del Menezzi [175], Çolakoğlu et al. [176], Jivkov et al. [177], Sinha et al. [178], Niu and Wang [179], Jamalirad et al. [180], Azahari et al. [181], Bodîrlău et al. [182], Engineering Toolbox [183], MatWeb LLC. [184], Jalalian et al. [185].

Material property	Mycelium composites		Synthetic foams		Wood products	
Density (kg/m^3)	+	59–552	++	PS: 11–50	−	PW: 460–680
			++	PU: 30–100	−	SW: 440–600
			++	PF: 35–120	−−	HW: 850–1030
Material cost ($US/kg)	+	0.07–0.17[a]	+	PS: 2.1–2.3	+	PW: 0.5–1.1
	+		+	PU: 8.2–10.4	+	SW: 0.7–1.4
			+	PF: 1.7–1.9	−−	HW: 3–11
Tensile strength (MPa)	−	0.03–0.18	−	PS: 0.15–0.7	++	PW: 10–44
	−		+	PU: 0.08–103	++	SW: ‖ 60–100, ⊥ 3.2–3.9
			−	PF: 0.19–0.46	++	HW: ‖ 132–162, ⊥ 7.1–8.7
Compressive strength (MPa)	−−	0.17–1.1	−−	PS: 0.03–0.69	++	PW: 8–25
			+	PU: 0.002–48	++	SW: ‖ 35–43, ⊥ 3–9
			−−	PF: 0.2–0.55	++	HW: ‖ 68–83, ⊥ 12.7–15.6
Flexural strength (MPa)	−−	0.05–0.29	−−	PS: 0.07–0.70	++	PW: 35–78
			+	PU: 0.21–57	++	SW: 9.9–11.5
			−−	PF: 0.38–0.78	++	HW: 10.3–11.5
Fire resistance	−	no silica: low	−−	PS: very low	−	PW: low
	+	50 wt% silica: high	−−	PU: very low	−	SW: low
			++	PF: very high	−	HW: low
Thermal conductivity (W/m·K)	+	0.04–0.18	++	PS: 0.03–0.04	−	PW: 0.3–0.5
			+	PU: 0.006–0.8	+	SW: 0.08–0.3
			++	PF: 0.03–0.04	−	HW: 0.2–0.5
Acoustic absorption (NRC)	++	>70–75%[b]	+	PS: 0.2–0.6	−	PW: 0.1–0.23
			+	PU: 0.2–0.8	−	SW/HW: 0.05–0.15
Moisture uptake (wt%)	−−	40–580	++	PS: 0.03–9	−	PW: 5–49
			−	PU: 0.01–72	−−	SW/HW: 5–190
			+	PF: 1–15		
Termite resistance	−	Low-moderate	−	Low, vulnerable to nesting	−	Low, excluding heartwood or treated wood
Production time	−−	Days-months	++	min-days	++	min-hours
Feedstock	++	Wastes, by-products	−	PS: styrene	+	PW: wood chips, resin
			−	PU: isocyanate, polyol	+	SW/HW: wood
			−	PF: Phenol formaldehyde resin		
Manufacturing process	++	Fungal growth		Polymerization and expansion		PW: lathing, pressing, resin infusion SW/HW: milling
Biodegradability	++	All constituents	−−	None	++	Wood constituents
Degradation time	++	Weeks-months	−−	Decades-centuries	+	Years-decades
End of life	++	Garden composting	−	Recycling, incineration, landfill	−	Recycling, incineration, landfill

NRC = noise reduction coefficient, with 0 indicating total reflection and 1 indication total absorption of sound. No noise reduction coefficient is available for mycelium composites. The mechanical properties of wood vary parallel (‖) or perpendicular (⊥) to the wood grain.
[a] Cost of raw materials only.
[b] Acoustic absorption at 1000 Hz.

wood products used in construction, with even heavy mycelium composites produced using pine shavings (87 kg/m^3) or red or white oak sawdust (300–552 kg/m^3) having lower or similar densities to plywood (PW, 460–680 kg/m^3), softwood (SW, 440–600 kg/m^3) and hardwood (HW, 850–1030 kg/m^3).

Mycelium composites are also cost competitive with both synthetic foams and wood products, with the raw material cost of mycelium composites, (0.07–0.17 $US/kg), constituting the cost of the agricultural and industrial by-products used to make them, much lower than the wholesale price of polystyrene (2.1–2.3 $US/kg), polyurethane (8.2–10.4 $US/kg), phenolic formaldehyde resin (1.7–1.9 $US/kg) foams and plywood (0.5–1.1 $US/kg), softwood (0.7–1.4 $US/kg) and hardwood (3–11 $US/kg) products. No data is available regarding the total manufacturing cost of mycelium composites, however because mycelium composites can be grown in ambient conditions and manufacturing simply constitutes dispensing a combination of steam sterilised agricultural by-product substrate and inoculum into a mould and waiting for full fungal colonisation, the raw material costs can be assumed to be the major component of the total cost.

Mycelium composites also have similar tensile (0.03–0.18 MPa), compressive (0.17–1.1 MPa) and flexural (0.05–0.29 MPa) strengths to polystyrene foams (0.15–0.7 MPa, 0.03–0.69 MPa and 0.07–0.70 MPa, respectively), but are weaker than polyurethane (0.08–103 MPa, 0.002–48 MPa and 0.21–57 MPa, respectively) and phenolic formaldehyde resin (0.19–0.46 MPa, 0.2–0.55 MPa and 0.38–0.78 MPa, respectively) foams. They are also much weaker than wood products, such as plywood (10–44 MPa, 8–25 MPa and 35–78 MPa, respectively), softwood and hardwood, although the mechanical properties of wood vary parallel (‖) or perpendicular (⊥) to the wood grain. Mycelium composites cannot be used in any structural applications traditionally achieved using wood, instead being more suitable for applications, such as door cores, or some panelling applications.

Mycelium composites do however have a significant advantage in terms of fire safety over traditional synthetic insulation materials, such as polystyrene and polyurethane foams, which are very flammable. Even mycelium composites comprising substrates containing no silica have better fire safety than these foams, with composites containing silica sources, such as rice hulls and glass fines, much safer than synthetic foams and even wood products, such as plywood, softwood and hardwood. In terms of fire resistance mycelium composites containing silica are outperformed only by phenolic formaldehyde resin foams which have exceptional fire resistance.

Realistically mycelium composites are best suited to compete with synthetic foams and wood products in thermal or acoustic insulation applications, where their combination of low density, low cost and fire resistance gives them a significant advantage. Mycelium composites produced from wheat straw or hemp fibers have low thermal conductivities (0.04 W/m·K) that can compete with polystyrene (0.03–0.04 W/m·K), polyurethane foam (0.006–0.18 W/m·K) and phenolic formaldehyde resin (0.03–0.04 W/m·K) foams. These values are also much lower than wood products, such as plywood (0.3–0.5 W/m·K), softwood (0.08–0.3 W/m·K) and hardwood (0.2–0.5 W/m·K), making them better thermal insulators than these wood products.

Despite no data being available regarding their noise reduction coefficient (NRC), mycelium composites have also been found to provide 70–75% acoustic absorption at 1000 Hz, which despite not being a parameter comparable with NRCs suggests that mycelium composites are likely to be competitive with the 20–60% absorption of polystyrene foams (NRC of 0.2–0.6) and 20–80% absorption of polyurethane foams (NRC of 0.2–0.8). These acoustic absorption characteristics are also likely to significantly outperform the 10–23% absorption of plywood (NRC of 0.1–0.23) and 5–15% absorption of wood surfaces (NRC of 0.05–0.15). It should be noted that application specific acoustic foams and wood products exhibiting superior performance are available, however since this assessment compares unmodified as-grown mycelium composites with traditional building materials, unmodified foams and wood products are assumed to provide a fair comparison.

The main disadvantage of mycelium composites for insulation applications is their moisture uptake (40–580 wt%), which is much higher than those of polystyrene (0.03–9 wt%), polyurethane (0.01–72 wt%) and phenolic formaldehyde resin (1–15 wt%) foams, and could be a serious problem in leaking wall or roof cavities. Even plywood, which has a significant moisture uptake capacity (5–49 wt%) still absorbs less water than mycelium composites, although normal timber also suffers from high water absorption characteristics (5–190 wt%) in addition to significant shape changes, such as warping. Like untreated wood products, mycelium composites also do not offer much termite resistance, which could be a problem in termite afflicted countries. However, it should be noted that synthetic foam, such as polystyrene, is also vulnerable to termite damage with termites sometimes establishing nests within the foam.

Another significant problem with mycelium composites compared to synthetic foams and wood products is their very slow manufacturing process, which takes days to months to complete compared to synthetic foams and wood products, which can be produced in minutes to days depending on their manufacturing and curing processes. These disadvantages are however perhaps offset by the environmental benefits of mycelium composites, which upcycle wastes and by-products into higher value materials using natural fungal growth, are fully biodegradable and can simply be composted in the garden over the course of a few months at the end of their life. In comparison, while wood products are also environmentally sustainable, synthetic foams require decades to centuries to decompose in the natural environment, are often not commercially viable to recycle and are instead incinerated for energy recovery.

5. Outlook and future applications of mycelium materials

Fungi continue to play a critical role in many aspects of life, from antibiotic medicines, to food products, such as beer, wine, bread, soy sauce, tempeh and meat substitutes. However, recent studies and commercialisation efforts have also demonstrated the significant potential of mycelium materials and mycelium composites, specifically in the areas of packaging [10,18,42,47,48], thermal insulation [10,36,37,106,107,117] and acoustic absorption foams [11,44,118] with fire resistant properties [34,91,131], in addition to panelling, flooring and furnishings [42–44,54]. The academic and industrial traction that this success has generated could see the widespread use of these materials in the construction sector in the future. The water absorption properties of mycelium composites are also generating interest as superabsorbent [186–188], while the hydrophobicity of mycelium material itself could see extension of mycelium-based films to coating [13,66] or textile [189] applications. Other applications of promise for mycelium stem from the chitin, chitosan and β-glucan polymers it contains. Extraction of these polymers for use in 3D printed structures, reinforcement for polymer nanocomposites, production of films, sheets and nanopapers [12] opens new doors in the replacement of synthetic polymers across these applications, which can in turn expand the use of mycelium into the realms of most products traditionally made from synthetic polymers, including filtration membranes [190], printed circuit boards [191], sports equipment and most other consumer products.

6. Conclusion

Mycelial growth provides a unique low energy bio-fabrication method to upcycle abundant agricultural by-products and wastes into cheap and environmentally sustainable alternatives to synthetic construction materials for applications, such as acoustic and thermal insulation, door cores, panelling, flooring, cabinetry and other furnishings. Acoustic and thermal insulation materials are typically highly porous and low-density materials, trapping air and attenuating sound waves, while door cores, panelling, flooring and cabinetry require scratch resistance (hardness), high flexural strengths and stiffness. Mycelium composites exhibit foam-like mechanical properties, which can be improved to resemble natural materials (e.g. wood and cork) and polymer materials (e.g. polyethylene and acrylonitrile butadiene styrene) through fungal species (continuous phase) and dispersed agricultural residue filler selection, physical processing (e.g. hot and cold pressing), resin infusion and hybridisation with materials, such as latex and cellulose. Mycelium composites are particularly well suited for thermal and acoustic insulation applications, exhibiting similar or lower thermal conductivities than commercial thermal insulation materials and 70–75% acoustic absorption or better, outperforming traditional ceiling tiles, polyurethane foams and plywood. They also exhibit better fire reaction and fire safety properties than traditional construction materials, such as extruded polystyrene insulation and particleboard and good termite resistance utilising natural termiticides. However, their typically foam-like mechanical properties, high moisture uptake and many gaps in material property documentation currently limit the application and usage of mycelium materials with further research and development of these materials necessary, in addition to targeted usage as non- or semi-structural supplements to traditional construction materials in specific, suitable applications, including insulation, panelling and furnishings. Nonetheless, the growing trends in the research and commercialisation of mycelium composite materials and their useful material properties makes them an effective, cheap and environmentally sustainable technology emerging with the potential to significantly contribute to the future of green construction.

CRediT authorship contribution statement

Mitchell Jones: Conceptualization, Investigation, Formal analysis, Writing - original draft. **Andreas Mautner:** Writing - review & editing. **Stefano Luenco:** Methodology, Writing - review & editing. **Alexander Bismarck:** Supervision, Writing - review & editing. **Sabu John:** Supervision, Writing - review & editing.

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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