



MYCELIUM-BASED COMPOSITES OVER TIME: MECHANICAL CHARACTERISTICS AND MANUFACTURING PROCESS

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ABSTRACT

Over the past decade, bio-fabrication has emerged as a pivotal component of sustainable construction strategies. Within this framework, mycelium biocomposites are particularly noteworthy; they consist of a vegetative organic structure formed by fungi in conjunction with substrates derived from agricultural waste. These biocomposites possess properties similar to expanded polystyrene while offering the significant advantage of biodegradability. The extensive versatility, scalability, and functionality inherent to mycelium have made it one of the most widely researched organic compounds in recent years. This study is a literature review of physical and mechanical studies of mycelium-based compounds over the past decade, presenting the information systematically by year and, at the end, a critical analysis that establishes comprehensive guidelines for the future. From the analysis conducted, a linear increase in compressive strength across various mycelium-based compounds examined by different researchers has been documented over the past decade, particularly in the most scrutinised species, *Pleurotus ostreatus* and *Ganoderma lucidum*; however, other species, including *Trametes versicolor*, also exhibit improvements in mechanical performance. Generally, this enhancement is attributed to the adoption of novel techniques and manufacturing processes, which have refined the methodologies used to develop new mycelium-based compounds.

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Introduction

Climate change, rapid population growth, urbanisation, industrialisation, and the economic development of the country's cities are leading indicators for modifying how and with what materials we build (Chandra Voumik & Sultana, 2022). For instance, there is a notable decrease in the useful life of buildings (Andreola *et al.*, 2020). Some studies suggest that the average useful life of buildings in China is 34 years (Liu *et al.*, 2014) and 25 years for residential buildings in Japan (Wuyts *et al.*, 2019). In contrast, the useful life of buildings in Latin American countries is estimated at 60 years, primarily due to a lack of regulations or guidelines that result in poor-quality living conditions and safety issues over time (Brito Garcia & Atalaya

Bazan, 2023). Despite this, buildings are being demolished prematurely more than ever, using valuable materials produced through energy-intensive processes that are costly or impractical to recycle because of the assemblies, coatings, and fastening systems they include. Considering all this, one of the main issues lies in materials based on fossil fuels; their versatility and cost-effectiveness make them the primary raw materials for construction by-products, such as floor and wall finishes, furniture, ducts, structural reinforcements, insulation, and sealants, to name a few. From manufacturing through their useful life, synthetic materials generate emissions harmful to the environment and human health.

The production of construction materials alone accounts for 38% of annual greenhouse gas emissions worldwide (United Nations Environment Programme, 2020). Based on this, the European Union has set climate targets to reduce greenhouse gas emissions by 20% by 2020 and 50% by 2050 compared to 1990 levels (Sartori & Hestnes, 2007). Furthermore, the Swedish Parliament has resolved that fossil fuels for heating must be phased out by 2020 and that CO₂ emissions must be cut by 40% from 1990 levels (Swedish National Environmental Objectives) (Chen *et al.*, 2001; Mithraratne & Vale, 2004). The building and property sector are recognised as an area with considerable potential to minimise energy use and its impact on climate change. According to Enshassi *et al.* (2014), “The construction sector is regarded worldwide as one of the main sources of environmental pollution, producing significant negative effects on the environment both directly and indirectly”.

On the other hand, non-plastic materials also present a problem. The aggregates used in concrete mixtures, sand, and gravel are permanently lost and transformed, often without the possibility of recovering them in their original form. In the case of sand, the relentless exploitation of this natural resource is already showing dramatic consequences (Hebel & Heisel, 2017). Examples of this are evident in the sand deficit in seabeds near coasts, which serve as a buffer for marine currents. As a result of overexploitation, these currents arrive with greater intensity, affecting coastal urbanisation. A similar situation occurs in lakes and riverbeds.

Furthermore, hundreds of islands are lost each year due to coastal erosion (Escóbar Llanos, 2002). The rapid growth of the world’s population has also led to increased demand for food and higher agricultural production, resulting in the generation of agricultural by-products and waste such as sugarcane bagasse, rice husks, cotton stalks, straw, and stubble (Bhuvaneshwari *et al.*, 2019). The combined generation of biomass waste in India and Southeast Asia alone amounts to one

billion tons annually (Tun *et al.*, 2019). Low-quality agricultural by-products and waste have limited applications. They are primarily used as fertilisers, animal bedding, and fillers for construction and road materials. However, they are mostly discarded as waste or burned, producing carbon dioxide and other greenhouse gases (Defonseka, 2014).

The vegetative growth of filamentous fungi, specifically mycelium has garnered increasing academic and commercial interest over the past decade as an innovative form of low-energy biomanufacturing and waste recycling (Jones *et al.*, 2017; Nawawi *et al.*, 2020). Mycelium binds organic matter through a network of hyphal microfilaments, a natural biological process that can be harnessed to produce low-value materials such as packaging, as well as higher-value composite materials from problematic agricultural products (Pelletier *et al.*, 2013; Haneef *et al.*, 2017; Jones *et al.*, 2017). Producing compounds from mycelium is a low-energy, carbon-neutral process that primarily benefits transforming the industry’s linear process into a circular one (Jones *et al.*, 2017). This means that, after use, these materials can be recycled and reused before their useful life ends (Vergara-Fernández *et al.*, 2016). These composites’ physical and mechanical properties are comparable to those of artificial foams, including acoustic panels, expanded polystyrene, and other insulating panels, making mycelium composites suitable for non-structural construction applications, particularly as insulating materials.

Mycelium composites are commercially available for these applications in the United States of America and Indonesia, although documentation regarding their physical and mechanical properties has not been publicly released (Ecovative, n.d.; Viniani *et al.*, 2022). Additionally, textile applications garner attention, with significant advancements in developing highly flexible mycelium-based polymer-like materials currently marketed through third-party designers as finished products rather than raw materials.

Research by Enarevba and Haapala (2023) estimates that the energy needed to produce mycelium and EPS is 6 MJ/kg (Stelzer *et al.*, 2021) and 42.4 MJ/kg (Hammond & Jones, 2008), respectively. A category impact analysis, which organises life cycle inventory data by their environmental impact contributions, revealed that EPS inserts have higher environmental impacts (Menglei *et al.*, 2022).

Over the past decade, mycelium has emerged as one of the most extensively researched organic compounds due to its diverse capabilities and potential for scalability and functionality. Pertinent studies provide insights into the current state of mycelium and its potential commercial applications (Universiti Putra Malaysia *et al.*, 2022); however, there is a paucity of research on the mechanical properties, which vary across processes, species, and substrates. At present, there exists no comprehensive, up-to-date compilation of essential mechanical studies to assist in standardising this material for commercial applications. This article presents a curated compilation (timeline) of mechanical studies on mycelium-based composites, facilitating

straightforward comparisons of information whilst highlighting their mechanical strengths and weaknesses.

Mycelium Structural Integrity

Fungi are organisms classified within the kingdom Fungi, the third central kingdom of life. It is estimated that there are around 50,000 species. We have only recently started recognising their role and importance on Earth. The life cycle begins with a spore measuring only a few microns (μm) in diameter. The spore swells in a humid, nutrient-rich environment (substrate), germinating into a tube that elongates into a filamentous, thread-like structure known as a hypha.

Figure 1 illustrates the growth and elongation of the hyphal-based structure over time, leading to a network of interconnected hyphal threads known as mycelium. When nutrients in the substrate become scarce, the mycelium ventures into the air and surrounding space to develop reproductive structures that eventually produce fruiting bodies, which generate sexual spores. Most of these fruiting bodies are commonly called mushrooms. These structures consist

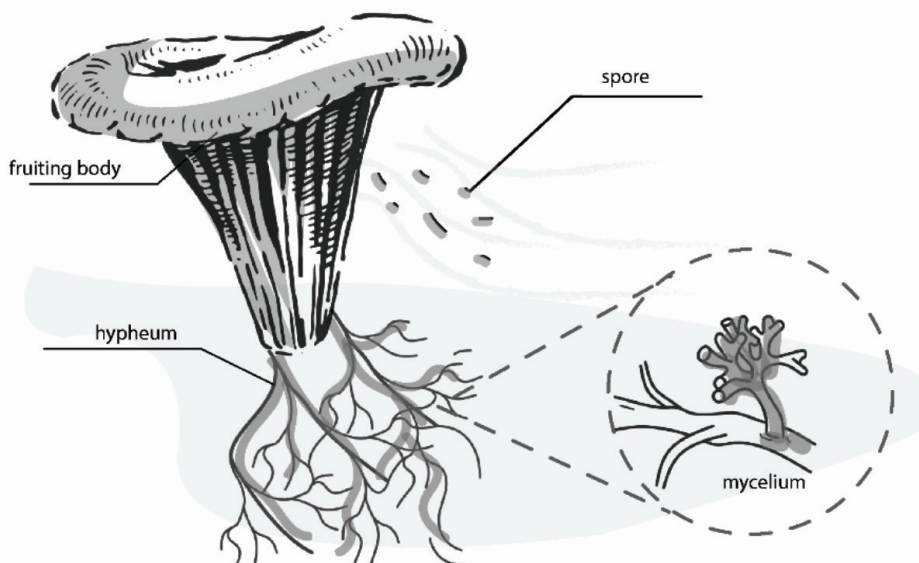


Figure 1: Components of a fungus and mycelial network. The hypheum network is usually covered with substrate as the fruiting body emerges to the surface

of more densely packed mycelia and differ in composition from the relatively loose mycelia found in the substrate, forming three-dimensional networks reminiscent of global interconnected computer systems. The diameter of fungal hyphae ranges from 2 to 10 μm , with fungal mycelium comprising a network of hyphae that vary in length depending on substrate availability and optimal growth conditions. The mycelium of mushroom-forming fungi can cover extensive areas, exemplified by the honey fungus, *Armillaria bulbosa*, which has spread across over 1,000 hectares of forest soil, making it the largest and oldest organism on the planet (Smith *et al.*, 1992). Additionally, mycelium from mushroom-forming fungi can also thrive on various by-products and waste materials from forestry and agriculture. The efficiency of colonisation and biomass formation is influenced by the substrate's composition and physical characteristics, as well as by growth conditions (temperature, humidity, and pH) and the genetic makeup of the fungus.

Unlike cellulose, the main structural polymer of plant cell walls, fungi represent a natural and renewable source of valuable structural polymers, including chitin and chitosan. Chitin is a linear macromolecule made up of N-acetyl glucosamine units, which is the primary component of the exoskeletons of most insects and other arthropods (Rinaudo, 2006). Fungal cell walls are found in hyphae that form mycelium, forming a fibrous, complex network based on chitin and other polysaccharides such as glucans, nanoproteins, chitosan, polyglucuronic acid, cellulose, and glycoproteins (Bartnicki-Garcia, 1968; Wessels *et al.*, 1990). These components confer mycelium mechanical properties characteristic of lignocellulosic materials such as wood and cork (Appels *et al.*, 2019). However, mycelium composites, which consist of a mycelium binder connecting a dispersed substrate fill phase made from agricultural waste, have lower densities and elastic moduli compared to pure mycelium and are typically classified as foams (Appels *et al.*, 2018). This is attributed to the air present

within and between the porous and less compact substrate filling (Holt *et al.*, 2012a).

Mycelium Manufacturing Environment

The substrate for mycelial growth is usually a mixture of wood residues and crop residues such as cotton, corn, wheat, hemp, and flax (Jiang *et al.*, 2017; Girometta *et al.*, 2019). These substrates are characterised by their high lignocellulosic content, which facilitates the growth of the fungus by allowing it to preferentially degrade cellulose or lignin in plant biomass (Girometta *et al.*, 2019). Cellulose is the most abundant natural polymer in hardwoods and crop residues. It provides the material for mycelial growth. Other substrates used are low-cost agricultural or forestry lignocellulosic by-products or wastes commonly used as fibrous substrates such as straw, or particulate substrates such as sawdust, to keep the cost of mycelium compounds low and facilitate waste recycling and the circular economy (Camere & Karana, 2018; Jones *et al.*, 2018). These substrates are cheap and sustainable but of low quality and have the side effect of limiting fungal growth, thereby compromising the composite's material properties. Although this compromise is acceptable for producing foam-like mycelial composites, higher-quality, more expensive substrates, such as nutritious wheat grains and sawdust, are sometimes used when mechanical properties are a priority (Xing *et al.*, 2018; Elsacker *et al.*, 2019).

The optimal temperature for mycelium cultivation is room temperature (24°C to 25°C) (Lelivelt, 2015). Additionally, the growing mycelium must be maintained in a relatively high-humidity environment. Therefore, humidifiers or sprinkler systems are typically utilised to promote mycelium growth. For instance, Jiang *et al.* (2017) established a high-humidity environment (up to 98% relative humidity) for mycelial respiration by employing a semipermeable polypropylene bag, which provides a humid, sterile environment for mycelial growth. After its natural growth, the mycelium contains a significant amount of water

(over 60%) (Elsacker *et al.*, 2019). This water must be removed to inhibit its growth and ensure high and reliable mechanical performance. Once the mycelium has fully colonised the substrate, processes must be implemented to dry the compound to halt the fungus growth sufficiently. The substrate and fungal species determine the final water content of the mycelium. For instance, a substrate made from hemp pulp absorbs more water than one made from cotton.

Additionally, various coatings can influence moisture absorption. The humidity before deactivation is typically reported as around 59% or 70% to 80% (Jiang *et al.*, 2017), but the residual percentage in the final material reported by researchers is roughly from 10% to 15%. Therefore, the water content of the resulting mycelium-based biocomposites is a primary consideration for the mechanics of mycelium samples.

In industry, manufacturing often employs plastic moulds filled with an organic substrate, which is incubated with mycelium to achieve the desired shape. Figure 2 illustrates how the *Pleurotus ostreatus* mycelium fully colonised the substrate and shaped itself according to the container mould.

explore techniques such as cultivating mycelium on a fibrous scaffold (Travaglini & Ross, 2016) using fibrous mats (R. Lelivelt *et al.*, 2015), 3D-printed cellulose scaffolds (Gil Martín *et al.*, 2014), or growing mycelium on mats or floating mats without fibrous content (Formela *et al.*, 2016). Previous studies have indicated the potential to develop a wide variety of products, including packaging, construction and insulation materials, transparent edible films, textiles, and leather-like products (Attias *et al.*, 2019).

Mycelium Mechanical Capacities

Compressive strength is the capacity of a material or structure to endure loads that tend to compress it. This trait is essential for a mycelium-based composite, which can be utilised in packaging and construction. The mechanical properties of mycelium-based biocomposites are vital for their application in engineering fields. The mycelium component is often criticised for its limited mechanical performance (Rippmann & Block, 2013). Nevertheless, recent studies examining chitin and glucan extracts derived from mycelium have found that they form a dense, robust matrix, exhibiting tensile strengths of up to 25 MPa, and for fruiting body extracts up to 200 MPa (Mohd Hanafiah *et al.*,



Figure 2: Sample of *Pleurotus ostreatus* mycelium fully colonised with sawdust substrate and shaped itself according to the container mould

2019). Reports indicate that the mechanical characteristics of a mycelial composite are primarily influenced by the fungal species, their productivity, the thickness of the mycelial fibres, the microstructure, and the surface topography, while the substrate secondarily influences them.

Flexural strength refers to the stress at the fracture point of a sample when bending. It is also known as the modulus of rupture, flexural strength, or transverse rupture strength. In comparison, the compression resistance is considerably higher than that of synthetic materials, ranging from 20 to 60 kPa. Later, Appels *et al.* (2019) reported the opposite result, achieving higher bending values of 66 to 72 MPa with hot and cold-pressing treatments using cotton or hemp substrates. This expanded the range of resistances and bending moduli obtained from unpressed fungal materials. However, several authors agree that higher material density results in a greater Young's modulus and strength, as observed in most cellular materials. The mechanics of mycelium composites appear quite different when comparing several studies.

Below are the main mechanical findings for Mycelium-based Composites (MBC) from the past decade to establish a temporal relationship between these studies.

Research Premises on Mycelium (2012-2016)

To address the mechanical capabilities of mycelium, it is essential to establish that the substrate is a critical variable affecting the density of MBCs. Generally, a higher proportion of grains (fibres, shells, or wood pulp) in the substrate leads to a higher density (Holt *et al.*, 2012b). These studies provide guidelines for future research in this field. Travaglini and Ross (2016) investigated the elastic and strength properties of mycelium bio-foam under both tension and compression. They found that strength decreases with increasing moisture content and that compressive strength is nearly three times that of tensile strength. In late 2016,

Travaglini and Ross (2016) manufactured mycelium bricks by mechanically pressing the inoculated substrate at least once during the growth process into a rectangular shape. When pressure is applied, the bond between the secondary materials and the fungal mycelium strengthens, resulting in higher density and improved resistance to compression and bending. Other research suggests creating mycelium sandwich panels similar to those developed by Travaglini, but manufactured with epoxy resins that adhere a central mycological matrix material to a top layer (a layer of woven carbon fibre textiles or a laminated layer), yielding encouraging results for future research.

Table 1 presents the mycelium-based compounds, manufacturing processes, applications, and regulations from 2012 to 2016. The data reveal that the most studied species is *Pleurotus ostreatus*, with the most commonly used substrates being hemp fibres, wheat, and various wood fibres. Additionally, manual pressing and plastic moulds are prevalent in all cases. The most common and effective sterilisation process occurs in an autoclave at 121°C for 15 to 20 minutes, while drying times vary widely, ranging from 50°C for 46 hours to shorter processes at 125°C for 2 hours. The incubation periods observed after mould inoculation ranged from 6 days post-demoulding for samples containing *Pleurotus ostreatus* to 30 days for those containing *Ganoderma lucidum*, a less aggressive species that therefore takes longer to colonise. The standards used include ASTM D-749 for density and apparent porosity tests, as well as ASTM D7250 and C393 for three-point bending tests. Lastly, the compressive strength values for the different species are low, ranging from 20 to 93 kPa and 4.6 to 17.9 MPa for bending stresses. Despite these mechanical results, the material's density ranges from 0.178 to 0.198 g/cm³, suggesting potential applications in the packaging industry and opportunities to replace other plastic materials during that period.

Table 1: Mycelium-based composites, manufacturing process, application, and regulations used (2012-2016)

Fungal Species	Substrate	Supplement	Moisture Content (%)	Temperature (°C)	Sterilisation	Incubation Period (Days)	Samples/ Mould Type	Dehydration Method	Manufacturing	References
<i>Ganoderma</i> sp.	Cotton carpel	Cottonseed shell and starch	-	21	-	6 ^b	Plastic mould	-	Manual pressing	Holt <i>et al.</i> (2012)
-	Rice husk + wheat grain (50 to 50%; 70 to 30%; 30 to 70%)	-	-	-	Autoclave 121°C/15 to 20 minutes	-	-	-	-	Arifin and Yusuf (2013)
<i>Coriolus versicolor</i> , <i>Pleurotus ostreatus</i>	Wood chips, hemp fibre, and hemp mat	-	-	-	18 samples lasted 100 minutes boiling; 3 samples were sterilised with 0.3% hydrogen peroxide	30 ^b	Plastic mould	-	-	Lelivelt <i>et al.</i> (2015)
<i>P. ostreatus</i>	Wheat, edible organic films, and xanthan gum	-	-	-	-	-	-	-	-	López Nava <i>et al.</i> (2016)
-	Jute, hemp, and cellulose	-	-	-	-	14	3 groups/21 samples	-	-	Jiang <i>et al.</i> (2016)

Note: “a” stands for the period before modelling and “b” stands for the incubation period after modelling.

The Mycelium Race Begins (2017)

Density is one of the essential factors that can affect the mechanical properties of MBC. Starting from this concept, Islam *et al.* (2017) test mycelium samples using a stochastic continuum model that accounts for density fluctuations, predicting global stress-strain curves in close agreement with experimental results in both tension and compression. On the other hand, Jiang *et al.* (2019) discussed the use of different fibres (fabrics) for MBC. Their results show that flax, rather than jute or cellulose, is more efficient for colonisation and produces higher mycelial yields. The ultimate strength and yield strength of samples produced with flax surface layers (35 and 27 kPa, respectively) are almost double that of samples produced with jute (20 and 12 kPa, respectively) or cellulose surface layers (16 and 15 kPa, respectively).

That same year, Hanef *et al.* (2017) evaluated the mechanical properties of fibrous mycelium films using *G. lucidum* and *P. ostreatus* to grow in pure cellulose broth (PDA) and cellulose-potato dextrose (PDB), from which four different combinations of the mycelium were obtained. In general, *P. ostreatus* fibres are stiffer (i.e., higher Young's modulus) than *G. lucidum* fibres, which have a lower critical stress. On the other hand, critical stress, the final stress level at breakage was hardly affected by mycelial species. It is also observed that PDB can make the mycelial fibrous film softer but more elastic, i.e., with a lower Young's modulus and a higher critical stress.

From the valuable contributions of different authors in 2017, in-situ experiments emerged, such as MycoTree, which was the centrepiece of the Beyond Mining–Urban Growth exhibition at the 2017 Seoul Biennale of Architecture and Urbanism, South Korea. The structure represents a provocative vision of how we can move beyond the extraction of our building materials from the Earth's crust to their cultivation and urban growth, how to achieve stability through geometry rather than material strength, opening up the possibility of using structurally weaker materials safely, and ultimately how regenerative

resources in combination with comprehensive structural design have the potential to propose an alternative to established structural materials for a more sustainable construction industry. Finally, during this year, mycelium boards were manufactured by Pelletier *et al.* (2013), who pressed the inoculated substrate into low-density boards under heat and high compression pressure to achieve the desired densities. The mycelium particle board, branded MycoBoard™, has applications in work surfaces, moulded furniture components, seat backs, architectural panels, door cores, and cabinets. MycoBoard™ offers an environmentally sustainable alternative to particleboard, plywood, and fibreboard, which are traditionally produced from pressed and extruded wood chips and synthetic resin.

Table 2 summarises the mycelium-based compounds, manufacturing processes, applications, and regulations used in 2017. It is observed that in 2017, the species *Ganoderma lucidum* was mainly studied. In contrast, the most common substrates were sawdust from different trees, wood pellets, and cellulose. Likewise, the most common sterilisation process involves autoclaving at 121°C for 15 to 30 minutes, while the drying process occurs at 60 to 80°C for 2 to 24 hours. The incubation time before mould was 4 to 12 days, and the incubation time in the mould was 6 to 20 days. On average, 21 to 30 samples were made per experiment; the dimensions of the samples used to measure compressive stress ranged from 50 x 50 x 50 mm to 200 x 200 x 160 mm. For tension samples, 200 x 6 x 3.5 mm samples were designed. It was also observed that the compression standard was ASTM D2166-13, and the bending standard was ASTM D3574. Finally, it was identified that the average compressive stress ranged from 170 to 1,200 kPa, while the elastic modulus ranged from 3.97 to 24 MPa.

Mycelium Consolidation Process (2018-2019)

In early 2018, the “grow it yourself (GIY)” concept of Ecovative (n.d.), an American company that distributes bags of substrate inoculated with dehydrated mycelium was

Table 2: Mycelium-based composites and manufacturing process (2017)

Fungal Species	Substrate	Supplement	Moisture Content (%)	Temperature (°C)	Sterilisation	Incubation Period (Days)	Samples/Mould Type	Dehydration Method	Manufacturing	References
White rot fungi, basidiomycete saprotrophic fungus (Alaska)	Sawdust pulp (Alaska birch 5 mm) and millet grain	Wheat bran	-	-	-	14	PVC tubular mould (5 × 6 cm) (30 samples)	60°C/24 hours	-	Yang <i>et al.</i> (2017)
						Tensile tests: 200 mm × 6 mm × 3.5 mm, Compression tests: 20 mm × 20 mm × 16 mm	-	Islam <i>et al.</i> (2017)		
<i>P. ostreatus</i> (Ecovative)	Wood pellets	-	-	-	-	4 ^a + 6 ^b	50 × 50 × 50 mm	80°C/24 to 48 hours (reduce water content to less than 10%)	Manual pressing	Heisel <i>et al.</i> (2017)
<i>Ganoderma lucidum</i>	Wood chips, sawdust, sugar cane, and cassava roots	-	60 to 65	28	Autoclave 121°C/30 minutes	8-12 ^a + 6-9 ^b	50 × 50 × 50 mm	80°C/24 to 48 hours (reduce water content to less than 10%)	Manual pressing	Heisel <i>et al.</i> (2017)
			70 to 80	25 to 30	Autoclave 120°C/15 minutes	20 ^b	0.4mm × 0.25mm, 0.1 to 0.3mm width	60°C/2 hours	-	Haneef <i>et al.</i> (2017)

Note: “a” stands for the period before modelling and “b” stands for the incubation period after modelling.

consolidated. Dry conditions preserve the hibernating mycelium, which is reactivated by adding water and wheat flour to the bags. The reactivated mycelium can be placed in user-defined shapes. Another significant contribution to this year was that of Islam *et al.* (2018), who explored the material's response to compression under cyclic deformation and developed an experimentally validated multiscale model for its mechanical behaviour. This model is beneficial because it can explore the effect of macro- and microscale density fluctuations on the overall mechanical behaviour and design mycelium-based products with the desired mechanical performance.

During this same year, Appels *et al.* (2019) evaluated the impact of environmental growth conditions and the deletion of the SC3 hydrophobin gene on the material properties of the mycelium of the fungus-forming fungus *Schizophyllum commune*. Based on these conditions, it was determined that Young's modulus (E) of the mycelium ranged from 438 to 913 MPa when the wild-type strain was grown in the dark under high carbon dioxide levels. This was accompanied by an ultimate tensile strength (σ) of 5.1 to 9.6 MPa. In contrast, E and σ of the strain lacking the SC3 gene were 3 to 4 times higher, at 1,237 to 2,727 MPa and 15.6 to 40.4 MPa, respectively. These values were correlated with mycelial density, without reporting differences in chemical composition; together, genetic modification and environmental growth conditions positively impact the mechanical properties of the mycelium by affecting its density.

Vidholdova *et al.* (2019) prepared mycelium boards from wood chip particles of between 5 and 10 mm to manufacture commercial particle boards (MDF-type chipboard) using the mycelium of the fungus *Trametes versicolor*. Despite poor workability under compression, the bonding strength of mycelium growth is equivalent to that achieved with synthetic resins, since the substitution of these bonding means is the main difference between mycelium boards and traditional particle boards. Furthermore,

using *T. versicolor* and five different types of fibres (hemp, flax, flax waste, softwood, and straw) and fibre processing (loose, chopped, powdered, pre-compressed, and tow), Elsacker *et al.* (2019) revealed that the mechanical performance of mycelium-based composites depends more on fibre processing and size than on the chemical composition of the fibres.

Finally, Appels *et al.* (2019) conducted cutting-edge research on mycelium, evaluating the visual appearance, density, mechanical properties, and water-absorption behaviour of MBC pressed from *P. ostreatus* and *T. versicolor*. The nine mycelium composites showed different behaviour under tensile stress, mainly depending on the pressing treatment, rather than on the substrate or fungus used. The heat-pressed samples had significantly higher tensile strength and elastic modulus than their corresponding cold-pressed and unpressed samples. The cold-pressed rapeseed and *Pleurotus* samples had a significantly higher tensile strength and elastic modulus than unpressed samples. The heat-pressed rapeseed and *P. ostreatus* straw material was rigid and strong but brittle; its tensile strength was high (0.24 MPa), and its breaking stress was relatively low (0.7%). Cold pressing the same substrate and mushroom combination yielded a material with much lower stiffness and tensile stress, but similar breaking stress. In conclusion, Appels *et al.* (2019) found that the tensile strength and elastic modulus of hot-pressed materials were higher than those of the corresponding cold-pressed and non-pressed materials. Likewise, they observed a similar trend during the three-point flexion. The flexural strength increased from unpressed to cold-pressed and hot-pressed. The unpressed materials presented flexural strengths ranging from 0.05 to 0.29 MPa and flexural moduli from 1 to 9 MPa. These data expanded the range of strengths and flexural moduli obtained with unpressed fungal materials.

Table 3 shows that, from 2018 to 2019, the variation in the species *Pleurotus ostreatus* and *Trametes versicolor* was studied due to promising results obtained in previous research.

Table 3: Mycelium-based composites and manufacturing process (2018-2019)

Fungal Species	Substrate	Supplement	Moisture Content (%)	Temperature (°C)	Sterilisation	Incubation Period (Days)	Samples/ Mould Type	Dehydration Method	Manufacturing	References
<i>P. ostreatus</i> (Ecovative)	Wood pellets	-	-	-	-	4 ^a + 6 ^b	200 mm × 6 mm × 3.5 mm; 20 mm × 20 mm × 16 mm	-	-	Islam <i>et al.</i> (2018b)
<i>S. commune</i> wild-type strain 4 to 39 (CBS 341.81) and its derivative ΔSC317	-	-	-	30	-	3 ^a + 6 ^b	-	3 rectangular mycelium samples (18 × 4 mm)	-	Appels <i>et al.</i> (2018)
-	Rice straw, fine rice powder, and sawdust	-	-	26 to 27	-	(7-15) ^a + 7 ^b	Plastic mould	1,000°C/30 to 45 minutes	-	B. Santosh <i>et al.</i> (2018)
<i>P. ostreatus</i> , <i>P. eryngii</i> , <i>Pycnoporus</i>	Fine coconut powder	Wheat bran	60 to 70	25	-	(15, 30, 45) ^b	-	-	-	J.L. Teixeira <i>et al.</i> (2018)
<i>Trametes versicolor</i>	Wood particles	Urea-formaldehyde glue, hardener, and paraffin emulsion	-	30 ± 2°C	-	21 ^b	6 samples of mycelium and 6 samples without mycelium of 250 mm × 180 mm × 2.5 mm width	60°C/8 hours	Three-stage pressing	Vidholdova <i>et al.</i> (2019)

<i>P. ostreatus</i> (Ecovative)	Particles of spruce, pine, and spruce	–	–	–	–	12 cm × 12 cm for compression; 12 cm × 3 cm for 3-point flexion	Cold-pressed using a 400 kPa hydraulic press; hot-pressed at 180°C for 15 minutes	Sun <i>et al.</i> (2019)
<i>P. ostreatus</i>	Sawdust, straw, and a mixture of both	Wheat bran	67.5 ± 2.5	24 ± 1	Autoclave 121°C/45 minutes	(5 × 5 × 5 cm ³) plastic and MDF formwork	6 hours using a fan, baked at 90°C/90 minutes	Ghazviniian <i>et al.</i> (2019)
<i>Trametes versicolor</i>	Flax, flax powder, treated long flax fibres, untreated long flax fibres, flax waste, wheat straw powder, and wheat straw	–	Water soaked for 24 hours	–	Autoclave 121°C/20 minutes	Compression testis: 75 mm PVC and a height of 37.5 mm	70°C/5 to 10 hours	Elsacker <i>et al.</i> (2019)
<i>P. sanguineus</i> , <i>P. albidus</i> , and <i>L. velutinus</i>	Sawdust	Wheat bran	–	–	–	–	–	Bruscato <i>et al.</i> (2019)

<i>Pleurotus ostreatus</i> , <i>Vohvariella</i> , <i>Polyporus squamosus</i>	Wood chips and hemp fibre	-	21	-	14 ^a + 7 ^b	48 brick samples of 6 design mixes, 200 × 90 × 60 mm	40°C/48 hours	Manual pressed with a spoon	Etinosa <i>et al.</i> (2019)
<i>T. multicolor</i> , <i>P. ostreatus</i>	1 to 3 cm beech sawdust and rapeseed straw, interwoven low-quality cotton fibre	Wheat bran	60 to 70	25°C	14 ^a + 10 ^b	Dog bone shapes for tensile tests (155 × 35 mm, neck 75 × 22 mm); bending tests (155 × 34 mm) and (45 × 45 mm)	80°C /24 hours	Hot (150°C) or cold (20°C) pressing was performed with a multiplate press for 20 minutes at F b 30 kN	Appels <i>et al.</i> (2019)

Note: "a" stands for the period before modelling and "b" stands for the incubation period after modelling.

The most studied substrates were particles and sawdust from different woods, since wood is the most common food source for the species studied. Likewise, using wheat bran as a supplement for the samples stands out because it improves growth performance, reducing colonisation times. It is also worth highlighting the use of flax fibres and waste in the research by Elsacker *et al.* (2019), which reported favourable results with different flax-based geometries. On the other hand, the most proposed sterilisation method was 121°C for 20 to 45 minutes, while the sample drying method varied between 60 and 80°C for 8 to 24 hours, indicating that drying time increases with temperature. During this research period, two hot and cold mechanical pressing methods were proposed, resulting in improved mechanical behaviour of the samples in most cases and expanding the mechanical range of mycelium-based compounds through their implementation. The standard chosen by the researchers was ASTM C165-07 (Vidholdova *et al.*, 2019), ASTM D1037 (Sun *et al.*, 2019), and ASTM D3501 (Elsacker *et al.*, 2019). Finally, it was identified that the compressive stresses varied between 140 and 1,300 kPa, whereas for bending, they ranged from 1.14 to 40.4 MPa (Appels *et al.*, 2019; Elsacker *et al.*, 2019).

Mycelium Knowledge Reinforcement and Innovation (2020-2021)

The attractiveness of mycelium as a sustainable material has generated diverse and innovative approaches by researchers, such as the proposal by Soh *et al.* (2020), which uses bamboo microfibres, chitosan, and *Ganoderma lucidum* mycelium to create an extrudable and buildable paste. The composition, tested under compression after 20 days of mycelial growth, produced a compression modulus of 40 kPa, compared to 240 kPa without chitosan. Despite the decreased mechanical properties, the composition has one advantage: The extrusion ability to create complex shapes. Within this field of innovation, Zimele *et al.* (2020) compared the mechanical properties of hemp and wood MBC against commercial materials (Ecovative® Design) (Ecovative,

n.d.), magnesium oxychloride concretes, hemp, and cemented wood wool panels manufactured by CEWOOD®, having resulted in a difference in bending strength of around 30%, with a better result for hemp samples. At the same time, the compressive strength was approximately 60% higher for the samples with wood than for those with hemp. Likewise, they are the first to propose biodegradation tests for 12 weeks, revealing mass loss of more than 70% for hemp and wood MBC, whereas for commercial products such as Ecovative, it was 60%.

On the other hand, it is known that all mycelia are hydrophobic, with contact angles with water of around 120°C, given these conditions, research by Antinori *et al.* (2020) suggests that glucose-preferring MBCs, such as *Ganoderma lucidum* in particular, become more brittle over time due to the influence that humidity has on this type of compound, given their porous nature and more suitable for absorbing moisture, knowing that water has a plasticising effect. For this reason, Antinori *et al.* (2020) propose a combination of glucose and lignin to obtain ductile mycelia but less porous in the specific case of *Ganoderma lucidum* MBC.

Another study that reinforces what was already carried out by Travaglini and Ross (2016) is the production of mycelium bricks by Maximino *et al.* (2020) from six design mixtures that consisted of rice bran (with and without mycelium), sawdust (with and without mycelium), and pure clay (with or without mycelium). As per the Indian Standard IS1077, all mycelium brick design mixes achieved adequate average compressive strengths and exceeded the minimum requirement of 3.5 MPa. Furthermore, they obtained higher compressive strength than their counterparts without mycelium, with an impressive increase of 38.5% and 31%, respectively, demonstrating that adding mycelium in the bending test improves the ductility of the brick specimens by producing fewer cracks. They also demonstrated that the mycelium's natural fibres acted as a binder for the building material.

Continuing the research, in 2021, Elsacker *et al.* (2021) investigated the mechanical properties of MBC produced with *Trametes versicolor* and supplemented with bacterial cellulose as an organic additive. Based on these conditions, they develop a methodological framework for producing bacterial cellulose and for the subsequent manufacture of hot-pressed mycelium composite particleboards. Their main finding is that adding bacterial cellulose to mycelium composites not only strengthens the internal bonding of the mycelium but also provides the material with tunable mechanical properties. In that same year, using *Ganoderma lucidum* mycelium grown on a substrate of sawdust and empty fruit clusters, Xin *et al.* (2021) demonstrated how climatic conditions affect the stress of dense mycelial compounds and the elastic modulus, testing the samples to the elements in tropical conditions for 35 days under flexural, tensile and compression loads regarding international standards. After exposure to specific climatic conditions, the maximum bending, tension, and compression stress decreased substantially. Adding a protective layer improved the resistance of the composites to weather conditions; however, the difference between the coated and uncoated samples was only found to be statistically significant in tensile strength.

Angelova *et al.* (2021) studied the potential of rose flower waste biomass and lavender straw as lignocellulosic feed substrates for the cultivation of *Ganoderma resinaceum*. Preliminary tests of their compressive behaviour yielded results ranging from 718 kPa to 1,029 kPa, demonstrating the viability of MBC for non-structural applications (Jiang *et al.*, 2017). As additional data for that year's research, it is established that adding barley as a supplement significantly increases the growth of highly studied species, such as *G. lucidum* and *P. ostreatus*, as reflected in their mechanical capabilities.

Table 4 shows that, from 2020 to 2021, the variation in the species *Pleurotus ostreatus* was mainly studied, with *Ganoderma lucidum*

Table 4: Mycelium-based composites and manufacturing process (2020-2021)

Fungal Species	Substrate	Supplement	Moisture Content (%)	Temperature (°C)	Sterilisation	Incubation Period (Days)	Samples/ Mould Type	Dehydration Method	Manufacturing	References
<i>Trichoderma asperellum</i> , <i>G. lucidum</i> , <i>Agaricus bisporus</i> , <i>P. ostreatus</i>	Oat and rapeseed hulls	-	-	-	-	-	12 to 14 mm and a thickness of 6 mm	-	Oil press	Z Tacer-Caba <i>et al.</i> (2020)
<i>P. ostreatus</i> , <i>P. citrinopileatus</i> , <i>P. eryngii</i> , <i>Ganoderma lucidum</i>	Psyllium husk, flour, and feathers	-	-	25	-	35 ^b	-	70°C/18 hours	Manual pressing	Silverman <i>et al.</i> (2020)
-	Sawdust and rice bran	-	-	25	-	7 ^b	Crystal glass	90°C/2 hours	-	Maximino <i>et al.</i> (2020)
<i>Ganoderma lucidum</i>	Cotton stem	Cotton bran	-	-	-	33 ^b	Steel mould	110°C to 115°C/24 hours	Hot pressing at 160°C and 10 mPa for 20 minutes	Liu X <i>et al.</i> (2020)
<i>P. ostreatus</i>	Xanthan gum and guar gum	Glycerol and molasses	65	25	-	7 ^b	Plastic mould	65°C/10 hours	-	Colmo <i>et al.</i> (2020)
<i>Trametes versicolor</i>	Hardwood and hemp chips	-	60 to 70	27	-	20 ^a + 30 ^b	Glass tank	-	-	Zimele <i>et al.</i> (2020)
<i>Trametes versicolor</i> , <i>Trametes multicolor</i> , <i>G. sessile</i>	Sawdust	Wheat bran	70 ± 5	22 ± 2	-	-	-	93°C	-	Attias <i>et al.</i> (2020)

<i>P. ostreatus</i>	Bagasse and sawdust	Wheat bran	50	23	-	6 ^a + 6 ^b	Plastic mould	60°C/48 hours	Loading pressure (10kg)	Joshi M. K. Meher <i>et al.</i> (2020)
<i>P. ostreatus</i> (Ecovative)	Sawdust	-	60	25	-	14 ^a + 14 ^b	Wooden mould	90°C/12 hours	-	Miralbes <i>et al.</i> (2021)
<i>Trametes versicolor</i>	-	Bacterial cellulose	-	-	-	-	40 mm ³	-	Hot pressed at 200°C	Elsacker, Vandeloock, <i>et al.</i> (2021)
<i>Ganoderma lucidum</i>	Sawdust and empty fruit bunch	Organic wheat grains	Wheat bran	-	-	-	-	-	-	Chan <i>et al.</i> (2021)

Note: “a” stands for the period before modelling and “b” stands for the incubation period after modelling.

and *Trametes versicolor* in the background. The most studied substrates were sawdust from different woods and hemp. Likewise, the potential of using barley bagasse as a supplement for samples in addition to popular substrates such as sawdust is highlighted (Soh *et al.*, 2020). On the other hand, the samples were dried at 40°C to 115°C for 2 to 48 hours. The growth periods ranged from 6 to 20 days prior to moulding and from 7 to 35 days after moulding and demoulding. During this research period, the two mechanical pressing methods (hot and cold) proposed by Appels *et al.* (2020) have continued to be used, improving the mechanical behaviour of the samples in most cases. The standards researchers chose were ASTM C67 (Tacer-Caba *et al.*, 2020) and ANSI A208.1-2016 (Liu *et al.*, 2020) for compression, while ASTM E518 was proposed for flexion. Finally, it was identified that compressive stresses ranged from 16.8 kPa (Tacer-Caba *et al.*, 2020) to 6500 kPa (Joshi *et al.*, 2020), while bending stresses ranged from 0.234 MPa (Miralbes *et al.*, 2021) to 1.1 MPa (Chan *et al.*, 2021).

Exploring New Design Technologies for Mycelium-based Compounds (2022-2023)

In the studies of Alemu *et al.* (2022), three substrates, namely sawdust, bagasse, and coffee husks, and the fungus *Pleurotus ostreatus* were used to develop MBC from PDA cultures. Mycelium growth on coffee husks had the fastest growth rate, while sawdust had the slowest. The fully colonised substrates were moulded with plastic moulds for 7, 14, and 21 days to maintain their regular 3D structure. The result shows that the block made with sawdust after 21 days of moulding has greater resistance to compression (750 kPa) and a density of 343.44 kg/m³, respectively, followed by bagasse and coffee husk. That same year, the material developed by Vasatko *et al.* (2022) demonstrated qualities suitable for compression structures, temporary assemblies, and acoustic and thermal insulation. Its methodology includes evaluating several lignocellulosic substrates, focusing on beech sawdust, using two strains of

mycelium (*Pleurotus ostreatus* and *Ganoderma lucidum*), and performing density calculations, compression tests, three-point bending tests, and capillary water absorption tests.

Özdemir *et al.* (2022) took a different approach, focusing on enhancing the structural performance of MBC for indoor use through manufacturing processes aided by a robotic arm for wood welding via an ultrasonic welding horn. They integrated wood fibres with various lattice variations in the mycelium matrix as reinforcement. The base materials included *Ganoderma lucidum* and hemp as the primary substrate, with maple veneer for structural reinforcement. Three-point compression, pull-out, and flexural tests were conducted to compare unreinforced and veneer-reinforced samples, revealing higher flexural strength in the reinforced samples.

Another innovative study that challenges conventional manufacturing techniques for MBC is the design method proposed by Nguyen *et al.* (2022), which aims to guide mycelium growth within a natural rattan frame serving as a support structure for the mycelium substrate and its fibre reinforcement. The rattan skeleton is integrated into the finished composite product, where both components are fused, resulting in a fully biodegradable unit. Using digital tools, the geometry of a structure designed to work in compression and capable of supporting more than 20 times its weight was calculated. In line with this knowledge, Rigobello's research (2022) proposes fibre placement strategies with three typologies: Rattan fibres perpendicular to the load, typical cane fibres coaxial to the load, and burlap coating coaxial to the load. The addition of coaxial fibre to the filler and the burlap covering significantly affected Young's elastic modulus and ultimate strength. Additionally, he suggests ASTM D1037 as the most appropriate candidate to support the design of specimens and the experimental plan for future MBC research.

Based on past research, we know that the MBC cultivation process involves multiple parameters that affect the material properties of the resulting material. For example, Ghazvinian *et al.* (2022) emphasise the role of substrate mixture and growing time in the material's mechanical behaviour. Their tests show that more potent substrates with higher lignin content such as sawdust, yield MBCs with higher compressive strength, whereas weaker substrates such as straw, yield MBCs with lower compressive strength. A direct correlation is observed between substrate density, MBC density, and the material's mechanical strength. At the same time, he reinforces the inverse relationship between cultivation time and the material's mechanical performance, taking samples of up to 49 days of total growth.

Using a granulometric approach, the studies of Irbe *et al.* (2022) developed new MBC mixtures from combinations of birch and hemp sawdust, with additives of birch bark and wheat bran, for *Trametes versicolor* growth. Among the most relevant findings, they determined that a larger granulometric fraction in hemp MBC resulted in higher strength but weakened water absorption (600% to 880%). Soh E. and Le Ferrand (2023) propose growing the mycelium in porous woodpile structures to increase the final mechanical properties. Using compounds derived from *P. ostreatus* and bamboo microfibre substrates, it was found that the porosity designed into the substrates increased the formation of a dense fungal mycelial skin. As a result, the stiffness of the porous structures increased 6-fold after 28 days of growth.

The most recent studies that seek the best compressive properties of MBC are the tests carried out by Peng *et al.* (2023), where different *Pleurotus ostreatus* compounds in different substrates, such as rice straw, bagasse, coconut fibre, sawdust, and corn straw, are comprehensively evaluated based on their growth, mechanical and hydrophobic

properties, with compounds derived from rice straw and bagasse exhibiting higher hydrophobic properties than others. Likewise, the research of Balaes *et al.* (2023) focuses on testing eight different substrates for seven strains of mycelium from different species, within these species are three of the most studied such as *T. versicolor*, *G. Lucidum*, and *P. ostreatus* (Tudryn *et al.*, 2018; Schritt *et al.*, 2021; Ghazvinian & Gürsoy, 2022). However, Balaes determined that the *Abortiporus biennis* strain produced the best compounds when mixed with small spruce sawdust particles and wheat bran as a reinforcing agent for mechanical properties, a finding previously verified by Schritt *et al.* (2021). These samples developed a highly hydrophobic surface material with a density as low as 0.255 g/cm³ and high strength, making it an excellent candidate for producing biodegradable packaging products.

Finally, the study by Nussbaumer *et al.* (2023) produced compounds using two species of white-rot fungi, *Trametes versicolor* and *Trametes pubescens*, with beech wood sawdust as the substrate, and part of the compounds was hot-pressed. Nussbaumer *et al.* (2023) demonstrated that material properties depend on hot pressing, revealing significant differences between pressed and unpressed samples. A clear example is the fracture work for *T. pubescens*, which decreased after pressing, unlike the samples of *T. versicolor*, whose fracture work increased after hot pressing. Additionally, it was shown that the water absorption of mycelial compounds at high relative humidity could be reduced by hot pressing. This study indicates that selecting fungal species may be crucial for hot-pressing mycelium composites.

Table 5 indicates that from 2022 to 2023, the variation in the species *Pleurotus ostreatus*, *Ganoderma lucidum*, and *Trametes versicolor* was primarily studied in equal measure. The most commonly studied substrates were sawdust from various types of wood, hemp, and bagasse, mainly because these substrates have consistently proven successful in previously proposed formulas. The most frequently utilised

sterilisation method was an autoclave set at 121°C for 20 to 60 minutes. Conversely, the drying method ranged from 50°C to 70°C for 10 to 48 hours; thus, it can be inferred that drying is more effective over extended periods and at lower temperatures. The growth periods varied from 3 to 14 days prior to moulding and from 3 to 28 days post-moulding and demoulding. Additionally, manual pressing was used in all studies, enhancing the mechanical behaviour of the samples. The researchers referenced ASTM D1037 (Rigobello & Ayres, 2022) and ASTM D3574 (Özdemir *et al.*, 2022). Lastly, it was noted that compressive stresses ranged from 270 kPa (Peng *et al.*, 2023) to 4,310 kPa (Vašatko *et al.*, 2022), while bending stresses ranged from 0.16 MPa (Peng *et al.*, 2023) to 4.1 MPa (Özdemir *et al.*, 2022).

Overall Discussion on the Mechanical Behaviour of MBCs

The values obtained by researchers over the years demonstrate consistency in terms of density and mechanical resistance, indicating significant improvements in workability and capacity. In terms of compressive strength, mycelium-based foams vary from 0.029 MPa to 0.567 MPa (Girometta *et al.*, 2019). However, notable values have been observed, ranging from 1.2 MPa (Jones *et al.*, 2018) to Haneef's reported 12 MPa in 2017 (Haneef *et al.*, 2017), resulting from the implementation of innovative manufacturing processes, including hot pressing, the incorporation of organic additives or bacteria, the arrangement of components, and the development of hybrid compounds that integrate mycelium with other materials.

Nevertheless, the flexural strength of mycelium-based materials exhibits substantial variability depending on the substrates utilised for fungal growth. For instance, Holt *et al.* (2012b) report flexural strength values ranging from 0.007 MPa to 0.26 MPa, while Jiang *et al.* (2017) provide values spanning from 0.0046 MPa to 0.18 MPa. Concurrently, Appels *et al.* (2019) discovered that mycelium-based composites (MBCs) presented flexural strengths

Table 5: Mycelium-based composites and manufacturing process (2022-2023)

Fungal Species	Substrate	Supplement	Moisture Content (%)	Temperature (°C)	Sterilisation	Incubation Period (Days)	Samples/Mould Type	Dehydration Method	Manufacturing	References
<i>P. ostreatus</i> and <i>Ganoderma lucidum</i>	Beech wood	-	60	28	Autoclave 120°C/20 minutes	7 ^a + 7 ^b , 21 ^b , 35 ^b	40 mm × 240 mm flexion; 25 mm × 195 mm dog bone (tension); 25 mm × 102 mm compression	-	Manual (arrangement of fibres in directions)	Rigobello and Ayres (2022)
	5 to 25 mm hemp fibres	Ventoux montmorillonite clay superfine powder	55 to 70	-	Autoclave 121°C/15 minutes	-	-	-	Hot pressed	Elsacker et al. (2022)
<i>Ganoderma lucidum</i>	Hemp	Maple veneer	60	26	Autoclave 121°C/20 minutes	12 ^a + 5 ^b	190 mm × 50 mm for flexion; 50 mm × 50 mm for perpendicular traction; 180 mm × 30 mm for parallel traction	70°C/10 hours	Hot pressed	Özdemir et al. (2022)
	Beech sawdust	Cellulose pulp, shredded cardboard, shredded newspaper, cotton fibres, soy silk fibres, and wheat bran	60	26 to 28	Autoclave 121°C/60 minutes	3-6 ^a + 3-5 ^b	5 cm ³ × 5 cm ³ × 5cm ³ in compression, 19 cm × 8 cm × 7 cm in flexion	60°C to 70°C/2 days	Manual pressing	Vašátko et al. (2022)

<i>P. ostreatus</i>	Sawdust, bagasse, and coffee husks	58	22 to 24	Autoclave 121°C/45 minutes	14 ^b	10 cm × 10 cm × 1 cm compression; 4 cm × 4 cm × 16 cm for 3-point bending resistance	Manual pressing	Alemu <i>et al.</i> (2022)
<i>Ganoderma lucidum</i>	Rapeseed straw	–	–	22 + 1°C	7 ^b , 14 ^b , 21 ^b	11 cm × 8 cm × 4 cm plastic mould	50°C/48 hours	Gauvain <i>et al.</i> (2022)
<i>T. versicolor</i>	Yellow birch wood veneers	58	30	–	21 ^b	EPS mould	65°C/24 hours	Sun <i>et al.</i> (2022)
<i>T. versicolor</i> , <i>T. pubescens</i>	Beech tree sawdust	80	28	–	18 ^b	–	–	Nussbaumer <i>et al.</i> (2023)
<i>P. Ostreatus</i>	Dendrocalamus asper bamboo microfibrils	–	–	Autoclave 121°C/20 minutes	9 ^a + 16 ^b	21 cm × 10 cm × 3.5 cm cardboard moulds	65°C/24 ^a /46 hours	Soh and Le Ferrand (2023)
<i>P. ostreatus</i>	Rice straw, bagasse, coconut fibre, sawdust, and corn straw	37,5	–	Autoclave 121°C/1 hour	14 ^b , 28 ^b	Silicone ice cube trays and measurements of 3 cm × 3 cm × 1 cm	–	Peng <i>et al.</i> (2023)

Note: “a” stands for the period before modelling and “b” stands for the incubation period after modelling.

ranging from 0.05 MPa to 0.29 MPa, along with flexural moduli ranging from 1 MPa to 9 MPa. The inconsistency in flexural values within the same species is rooted in the substrate, the most influential factor in this context.

In aggregate, mycelium-based materials demonstrate a lighter weight in comparison to alternative wood composites, including medium-density fibreboard (0.50 to 1.00 g/cm³) and oriented strand board (OSB) wood composite (0.55 to 0.70 g/cm³) [24]. In general, the density and Young’s modulus of mycelium materials align closely with those of natural materials and foams.

Among the study parameters, the most important are the substrate type, cultivation time, and mycelial species. These parameters are influenced by other equally relevant conditions such as the temperature and the size of the compound to be manufactured. In Figure 3, we can see that among the total number of articles investigated, 47% examined the species *P. ostreatus*, while 28% focused on *Ganoderma lucidum*. Regarding the substrate, the researchers’ primary choice was sawdust, followed by wood chips from various trees.

Results also indicate that fibre substrates such as hemp resulted in greater surface colonisation in a shorter time.

In contrast, samples with sawdust and straw particle substrates took longer to fully develop. However, they showed better mechanical properties, as is the case with *G. lucidum*, which mainly degrades lignin and hemicellulose before cellulose. These observations show that substrates play a key role in refining the desired physical and mechanical properties. The weight and density of the substrate largely determine the composite’s properties and, therefore, its mechanical capacity. Reported tensile properties exhibit considerable variability among studies concerning sawdust substrates; however, sawdust is generally associated with greater tensile strengths compared to straw substrates. Nevertheless, the tensile properties of cultivated sawdust-based mycelium composites do not correlate with the substrates’ mechanical properties. Table 6 shows the most commonly used substrates by loading type. Fibrous fibres work better for flexural and tension loading, while particulate substrates work better for compression loading.

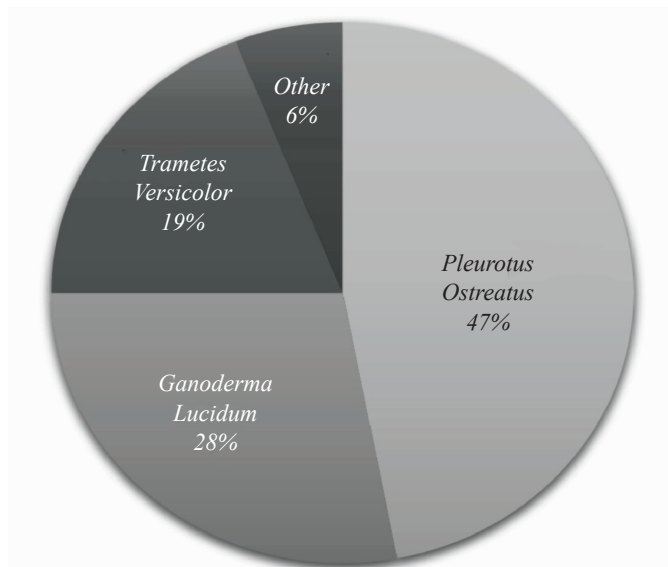


Figure 3: Fungal species with leading mechanical studies in the last decade
 Source: Attias et al. (2019)

Table 6: Density, tensile, compressive, and flexural material properties of as-grown mycelium composites comprising fibrous and particulate substrates

Loading	Substrate Type	Substrate	Data
Tension	Fibrous	Rapeseed straw	Appels <i>et al.</i> (2019)
	Particulate	Beech sawdust	Appels <i>et al.</i> (2019)
		Red oak sawdust	Travaglini <i>et al.</i> (2016)
Compression	Fibrous	Flax hurd	Elsacker <i>et al.</i> (2021)
		Hemp hurd	Elsacker <i>et al.</i> (2021)
		Wheat straw	Ghazvinian <i>et al.</i> (2019)
	Particulate	Pine shavings	Elsacker <i>et al.</i> (2021)
		Red oak sawdust	Travaglini <i>et al.</i> (2016)
		White oak sawdust	Ghazvinian <i>et al.</i> (2019)
Flexure	Fibrous	Cotton fibres	Appels <i>et al.</i> (2019)
		Rapeseed straw	Appels <i>et al.</i> (2019)
	Particulate	Beech sawdust	Appels <i>et al.</i> (2019)

Source: Mitchell *et al.* (2020)

Another important fact about substrates is their local availability, as most are derived from waste products from other industries such as carpentry and agronomy. Their availability will depend on the location where they are manufactured. Furthermore, standardising the substrates used in manufacturing MBC could be feasible, as most of the applications proposed by the authors are non-structural and therefore depend more on their shape for their final use. The most commonly used supplement was wheat bran, and the most prevalent sterilisation process was autoclaving at 121°C for 20 minutes. Additionally, the optimal humidity level was 60% at a temperature between 25°C and 30°C. This humidity percentage remained consistent within that temperature range. Despite the research conducted, much remains to be revealed about the physical properties of these compounds in combination with different substrates.

Table 7 provides a detailed breakdown of the total number of references along with their various manufacturing processes and mechanical results. From this table, it can be inferred that under compression stresses, the compounds of *P. ostreatus* support values ranging from 16.8 to 450 kPa. In contrast, those of *Ganoderma* were higher, ranging from 610 to 4,440 kPa, primarily

because *Ganoderma* species develop robust fruiting bodies that resemble extensions of the woody substrate. These physical properties are coupled with longer growth times and specific conditions required for this species, unlike *Pleurotus* species, which grow faster and pose lower contamination risks. A similar trend is observed for bending stresses: *P. ostreatus* yielded values between 0.17 and 1.018 MPa, while *Ganoderma* yielded values between 4.1 and 22.7 MPa.

Of the total studies investigated, 95% performed mechanical tests under compressive stress, 39% under flexural stress, and 9% under tensile stress. Likewise, 26% performed mechanical tests across three effort types, and only 34% provided density results. Regarding mechanical compression results, the overall average was 1,008.909 kPa, with the most frequent value at 30 kPa. As for flexion, the average result was 2.35 MPa, and the average sample density was 0.328 g/cm³.

Figure 4 illustrates the graphed compression results for various combinations of substrates, species, and manufacturing processes proposed by different researchers from 2015 to 2023. The mechanical outcomes have generally followed a linear trend.

Table 7: The most studied fungal species in the production of mycelium-based composites and their mechanical properties in compression, bending, and tension (2012-2023)

Fungal Species	Compressive Strength (kPa)	Tensile Strength (MPa)	Flexural Strength (MPa)	Density (g/cm ³)	References
<i>P. ostreatus</i> , <i>P. eryngii</i> , and <i>Pycnoporus sanguineus</i>	20 ± 10 to 40 ± 10	–	–	–	J.L. Teixeira et al. (2018)
<i>Trametes versicolor</i>	30	–	–	–	Vidholdova et al. (2019)
<i>Pleurotus ostreatus</i>	146	–	1.018	0.552	Ghazvinian et al. (2019)
<i>Trametes versicolor</i>	140 to 1,180	–	1.14 – 1.32	0.094 to 0.350	Elsacker et al. (2019)
<i>P. sanguineus</i> , <i>P. albidus</i> and <i>L. velutinus</i>	400 to 1,300	–	–	–	Bruscato et al. (2019)
<i>Pleurotus ostreatus</i> , <i>Volvarellia</i> , and <i>Polyporus squamosus</i>	452	–	–	–	Etinosa et al. (2019)
<i>P. ostreatus</i> , <i>P. citrinopileatus</i> , <i>Pleurotus eryngii</i> and <i>Ganoderma lucidum</i>	124.80 to 340.08	–	–	–	Silverman et al. (2020)
<i>Ganoderma lucidum</i>	2,510	–	–	–	Liu X et al. (2020)
<i>Trametes versicolor</i>	360 ± 50 to 520 ± 80	–	–	–	Zimele et al. (2020)
<i>Pleurotus ostreatus</i>	650	–	–	–	Joshi M. K. Meher et al. 92020)
<i>P. ostreatus</i> (Ecovative)	128	–	0.234	0.121	Miralbes et al. (2021)
<i>Trametes versicolor</i>	1,720 ± 590	–	1.1 ± 0.170	1208.38 ± 29.82	Elsacker Vandeloek et al. (2021)
<i>Ganoderma lucidum</i>	4,440 ± 2,240	1.55 ± 0.37	–	–	Chan et al. (2021)
<i>Pleurotus ostreatus</i> and <i>Ganoderma lucidum</i>	–	–	1.1	–	Rigobello and Ayres (2022)

<i>Trametes versicolor</i>	450 to 540	0.62	1.47	-	Elsacker <i>et al.</i> (2022)
<i>Ganoderma lucidum</i>	1,200	-	4.1	-	Özdemir <i>et al.</i> (2022)
<i>Pleurotus ostreatus</i> and <i>Ganoderma lucidum</i>	4,310	-	0.171	0.22 to 0.51	Vašátko <i>et al.</i> (2022)
<i>Pleurotus ostreatus</i>	750	-	-	0.343	Alemu <i>et al.</i> (2022)
<i>Ganoderma lucidum</i>	845 ± 90	-	-	-	Gauvin <i>et al.</i> (2022)
<i>Trametes versicolor</i>	1,740	-	-	-	Sun <i>et al.</i> (2022)
<i>T. versicolor</i> and <i>T. pubescens</i>	130 to 1,550	-	-	0.238 ± 0.014 - 0.515 ± 0.036	Nussbaumer <i>et al.</i> (2023)
<i>Pleurotus ostreatus</i>	450	-	-	0.356	Soh and Le Ferrand (2023)
<i>Pleurotus ostreatus</i>	270.31 to 456.70	-	0.16 - 0.54	0.249 to 0.336	Peng <i>et al.</i> (2023)

This trend primarily arises from changes in manufacturing processes proposed by researchers, such as Appels *et al.* (2019) and Elsacker *et al.* (2019), which involve hot and cold mechanical compression of the various samples. However, Appels *et al.* (2019) noted that this process is not particularly effective for all species; it is most successful for the well-studied species such as *Pleurotus ostreatus* and *Ganoderma lucidum* (Figure 3). Among these, *Ganoderma lucidum* shows the most favourable results from these techniques, which can be further enhanced by extending growth times, thereby improving mechanical properties and overall long-term performance. For these reasons, it is important to note that the behaviour of MBCs produced by *Ganoderma lucidum* follows an exponential rather than a linear trend.

Statistical Approach

This article also analyses the statistical methods used by different authors. Table 8 presents the most common statistical analysis used in different mycelium research studies, where ANOVA integration stands out with 80% preference among the authors; however, 10% of the literature uses randomised experimental designs, as in Alemu’s 2022 study, which chose a factorial method. This may be related to inaccuracies in the regulations and norms adopted by authors, as mentioned in the next section.

Normative Studies

Table 9 presents the regulations used in the current literature. There is still significant variation in methodology and regulations, as only two of the authors agree, so ASTM D1037 seems to be the ideal basis for experimental testing of this type of biomaterial.

MBC’s Potential to Replace EPS

Polystyrene has maintained a leading role in plastic packaging materials due to its excellent heat insulation, durability, and light weight.

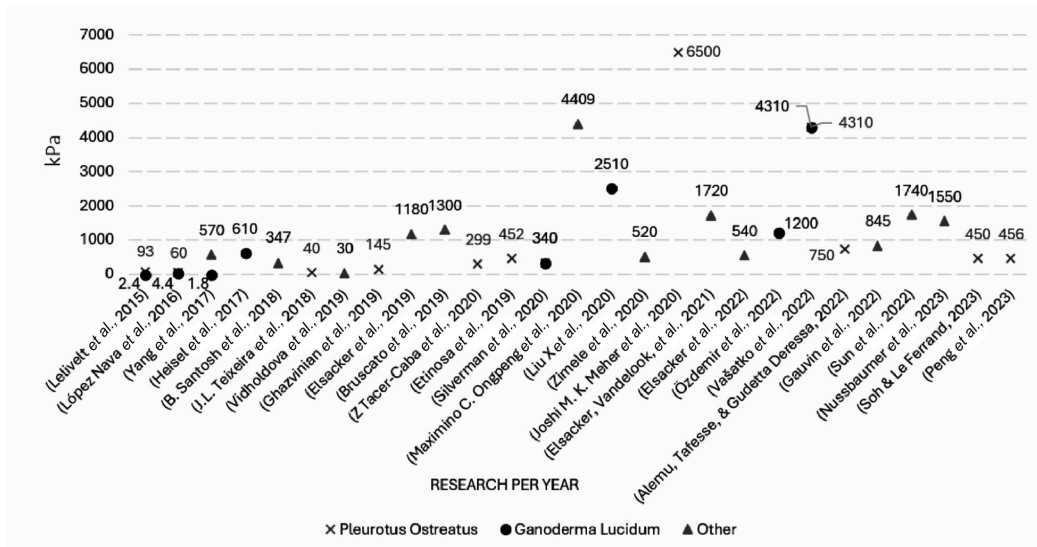


Figure 4: Compressive strength of MBC samples (2015-2023)

Table 8: Statistical analysis of MBC proposed by researchers (2012-2023)

Statistical Analysis Approach	Test	Reference
ANOVA	Pairwise Games - Howell test	Tacer-Caba <i>et al.</i> (2020)
ANOVA	–	Fufa <i>et al.</i> (2021)
ANOVA	SPSS version 26 software	Ejigu <i>et al.</i> (2022)
–	IBM SPSS Statistics 22.0 - Games-Howell	Appels <i>et al.</i> (2019)
ANOVA	IBM SPSS Statistics Version 23 - Duncan’s Multiple Range Test	Sun <i>et al.</i> (2019)
ANOVA-Tukey HSD	IBM SPSS Statistics 22.0 - a Games - Howell post hoc test - Kolmogorov–Smirnov test - Levene’s Test	Appels <i>et al.</i> (2020)
ANOVA	Microsoft Excel and graphed using GraphPad Prism (version 7.02) - Minitab	Jones <i>et al.</i> (2018)
Kenward–Roger method - Tukey family comparison - ANOVA	–	Nussbaumer <i>et al.</i> (2023)
ANOVA	Microsoft Excel and graphed with GraphPad Prism - Kolmogorov–Smirnov test	Elsacker <i>et al.</i> (2021)

Table 9: Regulations used in the manufacture of MBC (2012-2023)

Normative	Application	Reference
(ASTM D-749)	Density	Arifin and Yusuf (2013)
ASTM D7250 y C393	Dimensions of samples	Jiang <i>et al.</i> (2016)
ASTM Standard D2166-13	Compression strength	Yang <i>et al.</i> (2017)
ASTM D3574	Flexural strength	Heisel <i>et al.</i> (2017)
ASTM C 165-07	Compression and flexural strength	Vidholdova <i>et al.</i> (2019)
ASTM D1037 (2012)43	Compression strength	Sun <i>et al.</i> (2019)
ASTM D3501	Compression strength	Elsacker <i>et al.</i> (2019)
ASTM C67 y ASTM E518	Compression strength	Z Tacer-Caba <i>et al.</i> (2020)
ANSI A208.1–2016	Compression strength	Liu X <i>et al.</i> (2020)
ASTM D1037	Compression strength	Chan <i>et al.</i> (2021)
ASTM D1037	Compression strength	Rigobello and Ayres (2022)
ISO 29469	Flexural strength	Elsacker <i>et al.</i> (2022)
ASTM C578-18	Compression strength	Özdemir <i>et al.</i> (2022)
ASTM C578-18	Compression strength	Peng <i>et al.</i> (2023)

Nonetheless, these new mycelium advancements are setting a new standard and, hopefully, extend their use to large-scale applications across different industries. Table 10 shows companies that produce mycelium-based compounds for different applications. 16.66% of the companies work with generative food, 25% with packaging, 33.33% with biotextiles, 16.66% with education, and 8.35% in the construction sector.

Accordingly, global consumption of Expanded Polystyrene (EPS) exceeds 3 million tonnes, with an annual increase of 6% (Saltos *et al.*, 2015). However, the construction sector has not yet fully realised the benefits of mycelium. Construction plastic materials, such as EPS, are among the most widely utilised materials in contemporary construction, primarily serving as a lightweight agent in various construction systems, and demand for them is constantly growing. Although these plastic materials demand high energy consumption, they contribute significantly to air, water, and land pollution. The growth of mycelium on agricultural by-products and waste has attracted researchers seeking to develop low-energy

construction materials and explore waste-recycling opportunities (Madurwar *et al.*, 2013). Furthermore, mycelium-based materials offer numerous advantages over traditional materials, including reduced cost, biodegradability, and lower environmental impact and density. Utilising a broad range of substrates and controlled processing techniques facilitates the production of mycelium-derived materials with tailored structures and functions for specific applications. The bran or mycelium composites discussed here demonstrate competitive properties relative to expanded polystyrene (EPS), as illustrated in Table 11. EPS's flexural and compressive strength range between 0.07 and 0.69 MPa (Jones *et al.*, 2017).

Future Mechanical MBC Trends

To enhance the collective understanding of the mechanical properties of MBC and to advance towards mass production of these materials, further investigation is needed into the mechanical impacts of specific treatments such as gamma rays and waterproof films. In light of

Table 10: Commercial MBC’s applications

Company	Location	Industry
Ecovative	Unites States of America	Food
Design LLC	Unites States of America	Food
Ecovative	Unites States of America	Industrial design
Design LLC	Unites States of America	Biotextile
Mogu	Italy	Biotextile
Mycoworks	Unites States of America	Biotextile
Mycotech Lab	Indonesia	Biotextile
Radial	México	Industrial design
Loop Biotech	Neatherlands	Industrial design
Ecovative	Unites States of America	Construction
Mycomaker	Ecuador	Education
Self-made mycelium products	México	Education

Table 11: Comparison of MBC, strength, density, recyclability, and manufacturing method with expanded polystyrene EPS

Material Property	Mycelium-based Compounds	EPS
Density (g/cm ³)	0.22 to 0.51	0.01 to 0.045
Compressive strength (MPa)	0.029 to 0.567	0.07 to 0.69
Flexural strength (MPa)	0.05 to 0.29	0.07 to 0.69
Recyclability	Fully degradable	Decades, centuries
Raw materials	Mycelium and organic wastes or substrates	Polymers and natural gases
Manufacturing process	Moulding and growing	Polymerisation and expansion

these findings, a more comprehensive analysis of the mechanical characteristics of MBCs and the development of design implementation strategies is required to assess the functionality of mycelium mechanics in relation to the products final form and its direct interaction with other materials, such as concrete, similar to the systems employed in EPS vaults within traditional construction practices in Mexico and some Latin American countries.

Additionally, implementing less commonly used mechanical tests, such as abrasion, and exploring the material’s biodegradability are essential. Researching designs for

complex structures using various techniques, including reinforcement arrangement, extrudable pastes, and 3D printing is also vital. These experimental approaches are key for integrating mycelium-based composites into semi-structural applications or outdoor environments. Nonetheless, the growing research and commercialisation of mycelium composite materials, and their advantageous material properties, render them an effective, cost-efficient, and environmentally sustainable technology with significant potential to contribute to the future of green construction.

Conclusions

This review focuses on the mechanical properties of fungal-based materials over the past few years. Of the total studies investigated, 95% performed mechanical tests under compressive stress, 39% under flexural stress, and 9% under tensile stress. Likewise, 26% performed mechanical tests across three effort types, and only 34% provided density results. Regarding mechanical compression results, the overall average was 1,008.909 kPa, with the most frequent value at 30 kPa. As for flexion, the average result was 2.35 MPa, and the average sample density was 0.328 g/cm³. Mycelium-based composites offer mechanical advantages, are lightweight and environmentally friendly, but encounter significant limitations for large-scale use. For example, as biomaterials, their production lacks the standardisation seen in traditional engineering materials such as steel, cement, and polymers. It is essential to define how to tailor substrate types for different fungal species to enhance mycelial yield and improve mechanical properties. Moreover, it is vital to automate the regulation of growth factors—such as temperature, humidity, nutrition, and light—within the incubation environment, minimising reliance on human intervention during the growth phase. It is essential to understand these limitations before sharing the material with architects, engineers, or end users, and they also have broader industrial implications.

Recently, significant research and development of mycelium-bound composite materials, along with analyses of their physical and mechanical properties have shown potential to revolutionise the construction industry. Generally, researchers agree that fungal species from the *Basidiomycota* phylum, such as *Pleurotus ostreatus* and *Ganoderma lucidum*, are more effective in producing valuable compounds. These fungi have dense mycelium, grow quickly on readily available substrates, and possess a notable ability to degrade cellulose. This research suggests that sawdust and straw, commonly available in many countries, are among the best substrates for yielding high-

quality mycelium compounds. This analysis reveals a consistent increase in the compressive strength of various mycelium-based compounds studied by researchers over the past decade, especially in well-studied species such as *Pleurotus ostreatus* and *Ganoderma lucidum*.

However, other species, such as *Trametes versicolor* and *Multicolour*, also show a similar trend. This enhancement in mechanical performance over time is mainly due to the adoption of new techniques and manufacturing methods, which have improved the development of innovative mycelium-based compounds. While mycelium-based compounds may not inherently be getting stronger, advancements in manufacturing are facilitating broader applications that do not rely on structural integrity. Lastly, regarding standardisation, there remain significant variations among researchers, with only a single consensus between two authors on the ASTM D1037 standard, which is deemed the most suitable for initiating material standardisation. However, that is not the case for statistical analysis standards, where ANOVA methodology was preferred by 80% of the authors.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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