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Review

Variations in the Properties of Engineered Mycelium-Bound Composites (MBCs) under Different Manufacturing Conditions

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Abstract: Mycelium-bound composites (MBCs) are innovative materials created by combining lignocellulosic sub-products with fungal mycelium. These composites possess a remarkable ability to transform waste fragments into a continuous material without requiring additional energy input or generating further waste. The production process of MBCs involves utilising different fungal species, substrates, and pressing techniques, resulting in composites with diverse physical, mechanical, and functional properties. A comprehensive evaluation of MBCs' properties is crucial to explore their potential applications in the construction sector and ensure their suitability for specific purposes. This study provides a critical evaluation of the physical and mechanical properties of engineered mycelium-bound composites under various manufacturing conditions. Additionally, the analytic hierarchy process (AHP) and fuzzy comprehensive evaluation (FCE) methodologies were applied to investigation the optimum conditions for mycelium composites in the construction industry. The outcomes of FCE show the most promising fungal species, offering an optimal balance between material performance and production efficiency. Furthermore, the future development of MBCs manufacturing techniques was reviewed, providing a valuable reference for future research endeavours and showcasing the potential of MBCs applications within the field of civil engineering.

Keywords: mycelium-bound composites; advanced engineered biomaterial; manufacture conditions; fungi and substrate; mechanical properties

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1. Introduction

Managing greenhouse gas emissions and energy consumption to achieve climate neutrality has emerged as an important aspect within the construction industry's increasing emphasis on sustainable development [1–4]. Recent research indicates that the built environment is responsible for nearly one third of global carbon emissions, with a staggering 71% of these emissions resulting from the non-renewable energy utilised in the production of building materials [5]. Around 36% of Australia's carbon balance is contributed by the construction industry [6]. In response to these issues, governments have enacted policies aimed at reducing energy consumption and carbon emissions. The Paris Agreement, for instance, aims to limit global temperature rise to 1.5 °C, while the United Nations Framework Convention on Climate Change aims to achieve 100% net-zero emissions from new buildings worldwide by 2030 and net-zero emissions from all buildings by 2050 at the latest [7,8]. Utilising green-engineered materials instead of relying solely on conventional materials is a potential avenue to investigate. The production of conventional building materials, such as concrete and steel, requires substantial energy and leads to the emission of significant amounts of carbon dioxide. This could potentially lead to constraints on their extensive production and consumption in the future [9–11]. Biodegradable materials can be used for the production of complex geometries without the need for large amounts of energy, thereby reducing carbon emissions and simplifying complex disposal processes such as sorting, cleaning, and reprocessing [12]. Due to their efficient degradation properties and manageable recycling procedures, living materials have attracted significant attention. An example of such living material is mycelium-bound composites (MBCs), which provide advantages including low density, outstanding thermal and acoustic insulation properties, favourable interface behaviour, affordability, low environmental impact, and a reduced carbon footprint throughout its manufacturing and service life [9,13–18].

Mycelium-bound composites have numerous applications, including masonry, packaging materials, insulation panels, and inventive designs [19]. Several initiatives over the past three decades have demonstrated the expansion of the use of mycelium-bound composites in civil engineering [20]. In the 1990s, Phil Ross and Shigeru Yamanaka conducted experiments with paper and construction materials to investigate the potential of mycelium for bio-based materials, which marked the commencement of mycelium-bound material development [21,22]. To demonstrate the architectural potential of mycelium, several exhibition projects used the mycelium members, for example, the Hy-Fi Tower was erected in 2014 and the MycoTree was built in 2017 [23,24]. These efforts paved the way for future applications, such as Carlo Ratti's mycelium-bound structure growth and the 2019 construction of The Growing Pavillion [25,26]. Despite the growing prevalence of mycelium-bound composites in the construction industry, there is a lack of comprehensive evaluation guides that assess the properties of different varieties of MBCs manufactured under varied growth conditions [27]. In addition, the majority of current research focuses on individual variables, often neglecting comparative analyses of interconnected engineering factors. A more comprehensive exploration of multidimensional variables can aid designers in their material selection process, providing them with a thorough understanding of the balance between interconnected characteristics. To address this research gap, this paper conducts a comparative analysis of various mycelium composites, evaluating their specific strength ratio, strength-to-weight ratio, and specific modulus to determine their suitability for different structural applications. Moreover, a case study was undertaken to formulate a decision-making framework for the selection of secondary structural elements. The fuzzy comprehensive evaluation (FCE) method was used to systematically rank MBCs, and the analytic hierarchy process (AHP) was used to determine the relative weights of these evaluation factors, specifically in the context of non-primary structure members. The paper also reviewed the prospective advancements in manufacturing techniques for MBCs construction elements, encompassing possibilities such as 3D printing and the integration of additives to enhance MBCs' properties. This market outlook provides a valuable guide for researchers and underscores the significant potential of MBCs' applications across various fields.

2. Mycelium-Bound Composite Manufacturing

2.1. Fungal Species and Substrate Types

There are four main types of fungal species that can be used in the manufacturing of mycelium composites: white rot, soft rot, or brown rot as shown in Figure 1. Comparison of the growth conditions of these fungi revealed that brown rot fungi predominantly degrade cellulose, leaving behind a residue rich in lignin [28]. White rot fungi, on the other hand, have the ability to break down both lignin and cellulose in wood [28]. Soft rot fungi secrete cellulase in order to enzymatically break down cellulose in woody tissues [29], while the specific decay characteristics of the other listed species are unknown.

In recent decades, most researchers have primarily focused on the application of white rot fungi, with studies on species such as *Trametes versicolor*, *Pleurotus ostreatus*, and *Ganoderma* species being the most extensively researched. Soft rot and brown rot fungi, such as *Oudemansiella radicata* and *Lentinula edodes*, have also been studied for their potential application in mycelium-bound composites. Additionally, there have been fewer experiments conducted on other fungal species, such as *Coriolus* species and *Agaricus bisporus*, but they still demonstrate potential for the production of mycelium composites using locally available niche fungi. This differentiation highlights two main aspects of fungal research: the need for further investigation into the characteristics of commonly found and cultivated white fungi, and the exploration of feasibility and overall comparisons with other fungal species.

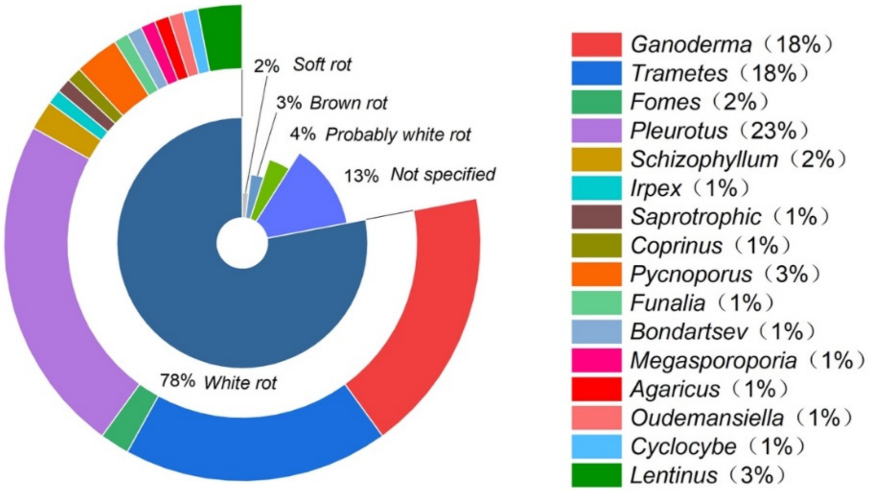

Figure 1. The different fungal species in MBCs.

In terms of substrate selection, agricultural waste materials like wheat straw, rice straw, maize stover, and sugarcane bagasse, as well as forestry by-products like sawdust and wood chips, are among the most frequently investigated substrates [21]. Furthermore, with the increasing output of industrial waste, the feasibility of utilising cellulosic materials such as cardboard, paper, cotton waste, and food waste (e.g., coffee grounds and spent grains) as substrates has been further explored [30]. The performance and characteristics of the resulting composite can be significantly influenced by the selected substrate type. The lignin content of the substrate can impact the strength and durability of the composite, while the carbohydrate composition can affect its water absorption and biodegradability [31]. In summary, regardless of the substrate type, they all need to be initially soaked in water for hydration, irrespective of their grade, as fungal development heavily relies on moisture [18,32,33]. Typically, the substrate requires a minimum soaking time of 48 h to ensure full water absorption but the specific duration of this stage varies depending on the substrate, as necessary [34,35]. This variability is one of the reasons why researchers explore various possibilities of substrates.

2.2. Growth Temperature and Humidity

Several crucial factors, such as temperature and humidity, influence the development of mycelium [9]. Mycelium-bound composites typically thrive and grow within a temperature range of 21 °C and 30 °C, with the optimal ambient temperature for mycelium growth being around 24 to 25 °C [36]. This indicates that mycelium can be readily cultivated at standard room temperatures. Specific fungi, such as *Pleurotus ostreatus*, often known as the oyster mushroom, may thrive at low temperatures ranging from 21 °C to 25 °C. As a result, these are appropriate for use in colder conditions or in applications where temperature control is difficult. Some fungi, such as *Ganoderma lucidum*, popularly known as the reishi mushroom, prefer a temperature range of 25 °C to 28 °C for maximum development [37]. Conversely, higher temperature elevation impedes development. At 35 °C, mycelium development was found to be slow, and at 40 °C, mycelium growth was absent [38].

In the context of humidity, optimal cultivation conditions for white rot fungi such as *Trametes versicolor* employed in the fabrication of mycelium composites generally encompass a range spanning from 70% to 80% [39]. However, brown rot fungi exhibit optimal growth within humidity parameters of above 95% [40]. Conversely, the growth rate of soft rot and other fungi is the fastest when the relative humidity is from 60% to 75% [41]. Mycelium growth requires a humid environment. The humidity level required for mycelium growth varies based on the type of fungus utilised. Figure 2 provides a summary of the various temperature and humidity ranges employed in different projects for the cultivation of mycelium-bound composites (MBCs). According to Figure 2, most mycelium species can grow within relative humidity (RH) levels ranging from 40% to 90%. Different fungi might have various optimal humidity values for growth and colonisation within this range. For example, *Trametes versicolor* is the form of fungus utilised in the development of mycelium-bound composites. According to Figure 2, this fungus grows well in a rather high humidity range of 70–90%. Nonetheless, following this phase of development, the samples must be desiccated to cease further growth and ensure uniform properties [21].

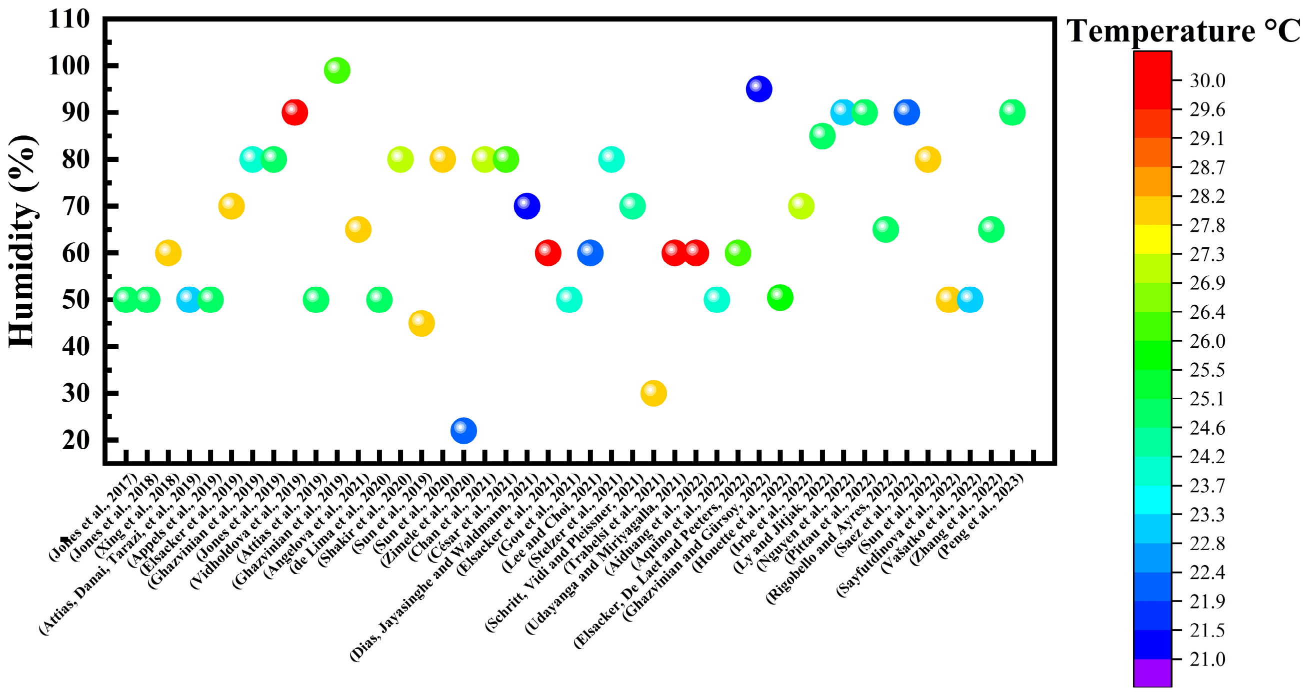

Figure 2. Growth temperature and humidity of MBCs [14,34,35,42–79].

2.3. Moulding System

The performance of mycelium-bound composite materials (MBCs) is significantly influenced by the chosen processing techniques, with cold pressing and hot pressing being the most commonly employed methods to enhance the physical and mechanical properties of MBCs [35,42,43,80]. Studies indicate that, when producing MBCs on various substrates using *Pleurotus ostreatus* and *Trametes multicolor*, the hot pressing process can increase the density of MBCs by an additional three times compared to the cold pressing process [43].

However, the choice of pressing temperature may vary depending on the substrate used. For instance, when producing mycelium-pressed boards, lignin softening occurs at around 115 °C [81]. However, if the pressing temperature is set at 120 °C, the thickness of the board may hinder effective heat conduction to the core during the pressing period. It is crucial to allow sufficient time for the material to cure properly, as inadequate curing time can significantly decrease the material's strength [82,83]. Lignin requires temperatures of approximately 160 °C to form new cross-links [84]. Conversely, another study proposed a different perspective, suggesting that increasing the pressing temperature to at least 160 °C can enhance the material's strength, but higher temperatures may weaken the binding strength of the mycelial hyphae [42].

To shape the structural members of MBCs into specific forms, different moulds are used. A commonly used method is to use wooden moulds to achieve the desired shape and size [44–48,78,85,86]. On the other hand, plastic moulds are also a popular choice [49–52,87,88]. In addition, some researchers wanted to produce MBCs with special shapes and therefore used metal moulds and acrylic glass moulds [53,54,65,89–91]. Elsacker et al. [55] innovatively formulated a comprehensive biological and digital fabrication pipeline that facilitated the growth of sizable mycelial composite blocks. The architectural scale demonstrated the potential for creating intricate forms using mycelium materials [55]. Their pioneering approach encompassed several key advancements, including the utilization of robotic wire cutting, employing mycelial material as a versatile template, and achieving self-repair capabilities within fungal organisms [55].

However, there is currently no established testing procedure for MBCs [38], and the different types of moulds may influence product performance. For example, high air content significantly impacts materials in moulds by resulting in decreased thermal conductivity [35,92,93]. Moreover, elevated porosity occurs due to void spaces amidst the fibres [94]. In seeking to unravel the diverse process parameters, encompassing fungal morphology, feedstock variations, processing conditions, and mechanical material properties, it becomes evident that intricate interdependencies interlink this array of factors [80,95].

3. Physical and Mechanical Properties of MBCs

3.1. Density and Water Absorption

The density and water absorption of MBCs are two key physical properties that can impact the material's overall characteristics [96]. High-density materials typically offer greater strength and durability for applications that require structural stability and durability. In contrast, water absorption indicates the ratio of water absorbed by a material to its initial dry mass under specific conditions. Materials with lower water absorption rates have better water and weather resistance. Density and water absorption are therefore important parameters to be considered together when developing and evaluating MBCs.

Figure 3a,b shows the density and water absorption of different fungal species and substrates. MBCs can be cultivated on wood-based substrates like pine and beech sawdust with a density of 25–350 kg/m^3. The density of MBCs varies from 25 to 437 kg/m^3 on agricultural crop residue substrates such as rapeseed straw, oat husk, and rice hull. MBCs grown on decomposed mushroom compost also have a density of 183–195 kg/m^3. Certain MBCs exhibit noteworthy densities. For instance, Chinese albizia sawdust has a substantially greater density than other wood-based substrates, with mycelium cultivated on it reaching a density of 954 kg/m^3. Lavender straw has a density of 347 kg/m^3, which is greater than the densities of other agricultural waste substrates like wheat straw and cotton stalk where mycelium is cultivated. Furthermore, the density of MBCs is influenced by a range of parameters, including fungal species, moisture content, temperature, and the specific fungus species utilised in the production process. MBCs produced using *Coriolus* species and *Ganoderma* species on apple wood chip, for example, exhibit a density range of 180–220 kg/m^3. On the other hand, *Pleurotus ostreatus* grown on rice husk yields a density of 437 kg/m^3. The same fungal species grown on different substrate types will yield different densities of MBCs. It can be concluded that the density of MBCs can significantly vary depending on substrate types and culture conditions.

The findings regarding the water absorption capacities of various fungal species across different substrates underscore the diverse nature of mycelium-bound composites (MBCs) and their interaction with distinct materials. Further investigation into the specific structural and compositional attributes of the fungal mycelium could shed light on the observed discrepancies in water absorption. *Trametes versicolor* exhibits notable water absorption capabilities in wheat straw and flax, with percentages of 26.8% and 30.3%, respectively. *Trametes multicolor*, on the other hand, shows a very high capacity to absorb water on rapeseed straw, with a percentage of 436%. *Pleurotus ostreatus* shows a modest ability for water absorption on rice straw, sawdust, and several kinds of rapeseed straw. The hydrophobic properties of the mycelial cell wall may contribute to the exceptionally low water absorption capacity of 6% displayed by *Ganoderma lucidum* on beech sawdust. In corn husk, rice straw, and sawdust, however, *Ganoderma fornicatum* and *Ganoderma williamsianum* show great water absorption capability. Wood materials, coconut products, and fibre materials substrates often have greater water absorption capacities, whereas miscellaneous substrates typically have lower water absorption capacities. It can be inferred that the water absorption ability of MBCs varies with the density of the growing substrate, which normally has high-density levels and low water absorption ability [97]. Additionally, water absorption in MBCs is not solely determined by the type of fungi or substrate, it is a complex interplay between mycelium growth, structural characteristics of the substrate, and environmental conditions. This complexity necessitates a deeper exploration beyond categorical distinctions.

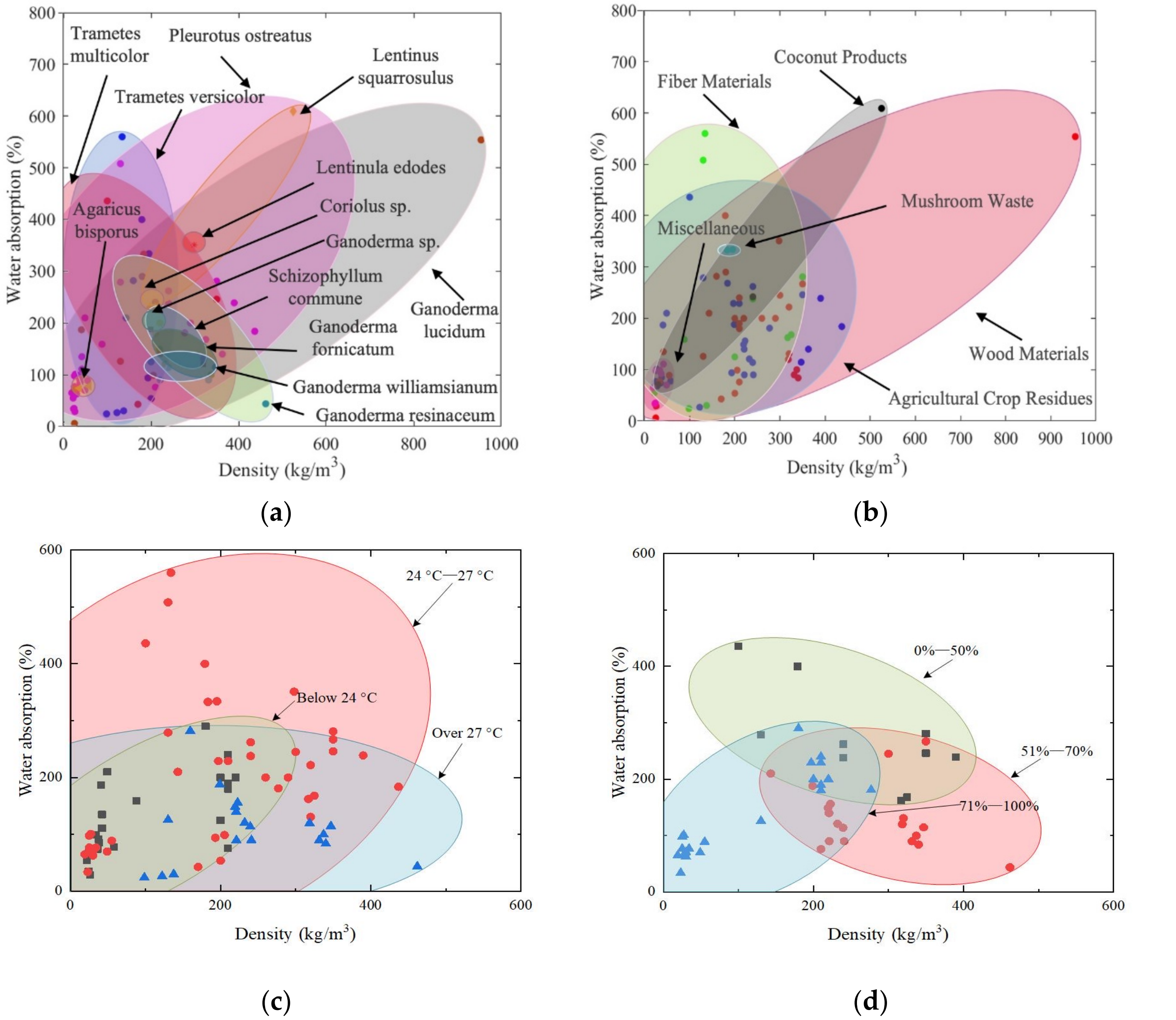

Figure 3. The density and water absorption of different (**a**) fungal species, (**b**) substrates, (**c**) temperature, and (**d**) humidity.

The density and water absorption characteristics of mycelium-bound composites (MBCs) exhibit notable variations under distinct temperature and humidity conditions. Figure 3c,d shows the density and water absorption of different growth conditions. MBCs grown at temperatures surpassing 27 °C, in conjunction with a relative humidity range of 51–70%, showcase the highest density. This outcome suggests that higher temperatures within this specified humidity range might favour the growth and compaction of mycelium networks, resulting in a more densely packed composite structure. In contrast, MBCs cultivated at temperatures below 24 °C and a relative humidity of 71−100% display the lowest density. Regarding water absorption, MBCs display their maximum capacity for absorbing water when developed in environments with temperatures ranging from less than 24 to 27 °C, alongside a relative humidity of 0−50%. This finding implies that moderate temperatures alongside relatively lower humidity levels foster MBCs' ability to absorb and retain water, potentially owing to the porosity and hygroscopic nature of the mycelium matrix.

3.2. Compressive, Flexural and Tensile Strengths

An essential mechanical characteristic that can serve as a vital factor in the development of functional materials is compressive strength [21]. The wide spectrum of compressive strengths observed across different fungal species and substrates illuminates the nuanced potential of mycelium-bound composites (MBCs) for diverse applications. Figure 4a,b shows the average compressive strength of different fungal species and substrates. *Trametes versicolor* has a compressive strength of 0.25 MPa on hemp hurds and a compression value of 0.05 Mpa on rice husk, highlighting its adaptability to different lignocellulosic substrates. *Pycnoporus sanguineus* demonstrates an average compressive strength of 0.73 Mpa, whereas *Pleurotus ostreatus* and *Ganderma lucidum* display the highest value of around 1.41 Mpa, indicating their potential suitability for load-bearing applications. In pine sawdust, other *Pleurotus* species, such as *Pleurotus albidus*, have lower compressive strengths of 0.4 Mpa. Using pine sawdust and peach palm sheath, *Lentinus velutinus* and *Lentinula edodes* demonstrate strengths of 1.3 Mpa and 0.22 Mpa, respectively. Notably, wood-based substrates consistently yield higher strengths, reflecting the compatibility of fungal species with such materials. Using rapeseed straw and sawdust, *Fomes fomentarius* and *Schizophyllum commune* demonstrate compressive strengths of 0.25 Mpa and 0.81 Mpa, respectively. On rice husk, rice straw, and coconut husk, *Lentinus squarrosulus* demonstrate compressive strengths of 0.46 Mpa, 0.54 Mpa and 0.47 Mpa, respectively. *Oudemansiella radicata* and *Agaricus bisporus* exhibit the lowest values, 0.09 Mpa and 0.13 Mpa, respectively. Nevertheless, growth conditions also affect the compressive strength of MBCs. Nashiruddin et al. [38] compared the effect of different temperatures, spawn loading, and substrate moisture content on the compressive strength of mycelium-bound biofoam (*Pleurotus ostreatus* grown on rice husk). The results showed that such MBCs had the highest compressive strength at 30 °C, 40 wt% spawn loading, and 50 w/w% substrate moisture content [38]. Therefore, the adaptability of various fungi to diverse substrates underscores the significance of substrate selection in material development. The varying strength of different fungal species on various substrates provides valuable insights for the selection and development of suitable materials across a range of applications, including construction and packaging.

Flexural strength is another key mechanical characteristic to consider while using MBCs [96]. In Figure 4c,d, the average flexural strength values for different types of MBCs reported in the literature are presented. *Ganoderma resinaceum* and *Ganoderma lucidum* show greater flexural strengths ranging from 1.25 to 2.5 MPa, while *Ganoderma fornicatum* and *Schizophyllum commune* show comparatively low flexural strength values ranging from 0.04 to 0.08 Mpa. Flexural strengths of MBCs produced from *Pleurotus ostreatus*, *Lentinus sajor-caju*, and *Ganoderma williamsianum* range from 0.2 to 0.26 Mpa. Substrate variability significantly impacts flexural strengths; the average flexural strength value of MBCs manufactured from various type of substrates, such as agricultural crop residues, fibre materials, coconut products, and miscellaneous is around 0.25 Mpa. The wood materials demonstrated the highest average flexural strength value, which is around 1.03 Mpa. However, it is worth noting that the flexural strength of MBCs is greater than that of synthetic polymer foam [43]. These findings highlight the range of flexural strengths exhibited by different types of MBCs, which can provide an environmentally friendly and sustainable alternative to synthetic materials, particularly when compared to synthetic polymeric foams. This suggests that MBCs have the potential to meet the performance criteria of demanding applications while offering environmentally sustainable solutions, underscoring their potential for revolutionising construction practices and mitigating the environmental impacts associated with traditional building materials.

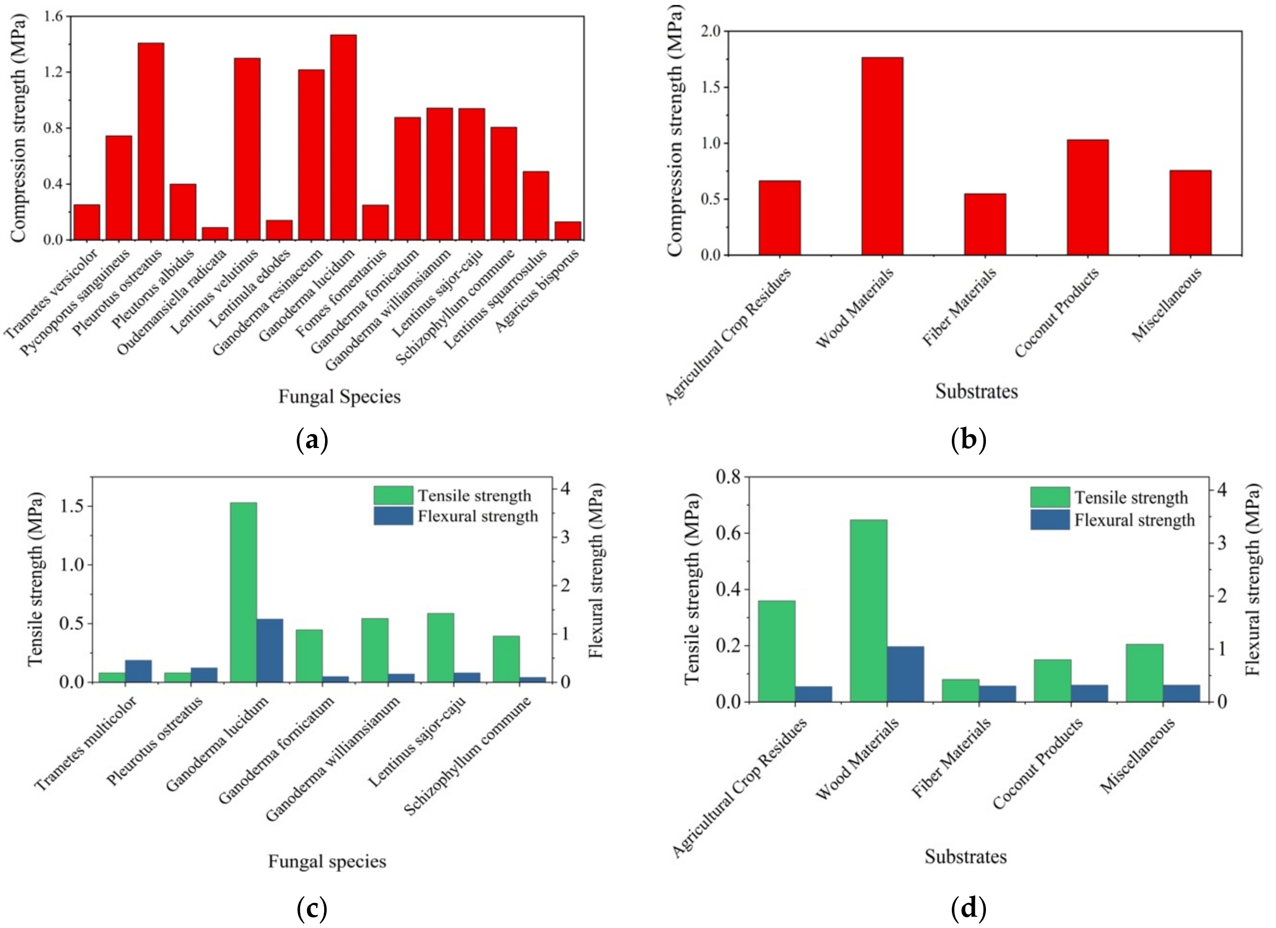

Figure 4. The average values of mechanical property of MBCs: (**a**) average compressive strength values of different fungal species, (**b**) average compressive strength values of different substrates, (**c**) average flexural strength and tensile strength values of different fungal species, (**d**) average flexural strength and tensile strength values of different substrates.

The tensile strength of MBCs can vary depending on the precise formulation and testing circumstances. When reinforced with rapeseed, cotton, and wheat straw, *Trametes multicolor* and *Pleurotus ostreatus* were found to have the lowest average tensile strength values ranging from 0.01 to 0.19 Mpa. When mixed with wood materials, *Ganoderma Lucidum* shows the highest average tensile strength value of 1.55 Mpa. When reinforced with sawdust, corn husk, and rice straw, *Ganoderma fornicatum*, *Ganoderma williamsianum*, *Lentinus sajor-caju*, and *Schizophyllum commune* show average tensile strength values ranging from 0.34 to 0.5 Mpa. These findings highlight that the tensile strength of MBCs is influenced by a variety of factors, including the specific growth conditions, the type of fungus used, and the type of substrate. It is vital to carefully consider these factors when formulating and testing MBCs to ensure that the desired tensile strength properties are achieved. Consequently, to advance the field and optimize MBCs for broader industrial applications, future research should delve deeper into understanding the microscopic characteristics of mycelial growth, the interfacial properties between the mycelium and substrates, and the influence of these factors on the material's mechanical behaviour.

3.3. Young's Modulus

The diverse range of Young's modulus values exhibited by mycelium-bound composites (MBCs) across various fungal species and substrates underscores the nuanced influence of formulation and testing conditions on their mechanical properties. The reported values for MBCs (Figure 5) have shown that the average Young's modulus values of different fungal species range from 6 Mpa to 77 Mpa, and the substrate range from 23 Mpa to 43 Mpa. The MBCs grown on agricultural crop residues substrates by *Ganoderma lucidum* were found to have the highest Young's modulus value and hence, had better mechanical strength and stiffness. However, it is crucial to note that Young's modulus can be significantly impacted by external factors like humidity and temperature, which contribute to the observed variability. For more information, the mechanical properties of MBCs with different fungal species and substrates are shown in Appendix B.

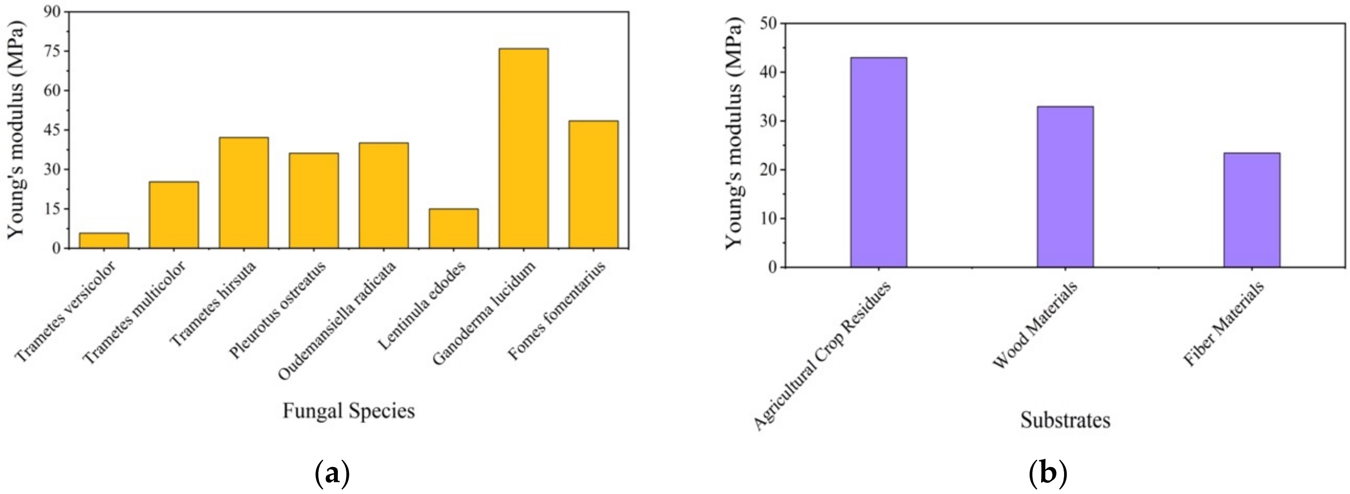

Figure 5. Average Young's modulus value of different (**a**) fungal species and (**b**) substrates.

4. Considerations for Structural Applications

The relationships between strength and density, strength and weight, and modulus of elasticity and density for different types of fungal species have been investigated in the literature through three ratios: specific strength ratio, strength-to-weight ratio, and specific modulus. The variations in specific strength ratio, strength-to-weight ratio, and specific modulus values across different fungal species highlight the importance of careful material selection and engineering. *Pleurotus ostreatus* stands out for its high specific strength ratio and specific modulus, suggesting its suitability for lightweight but strong structures and potential use in applications requiring materials with high stiffness. *Trametes versicolor* exhibits a high strength-to-weight ratio, making it a potential candidate for applications that prioritise strength and weight efficiency. These findings help to understand and advance the use of MBCs in a variety of industries where optimising strength, weight, and stiffness are key considerations.

4.1. Specific Strength Ratio

The specific strength ratio is the ratio between the strength of a material and its density. The higher the specific strength ratio of a material, the greater the strength that the material can provide for a given mass. Furthermore, the specific strength ratio analysis facilitates the identification of fungal species and MBCs formulations that exhibit superior strength-to-density efficiency. This knowledge enables researchers and industry professionals to focus their efforts on optimising these materials for specific applications. By refining the manufacturing processes, incorporating suitable reinforcement techniques, and tailoring the substrate composition, the specific strength ratio of MBCs can be further enhanced.

Specific strength ratio values were determined for various fungal species of MBCs and traditional materials in Figure 6. Fungal species like *Pleurotus ostreatus* exhibit specific strength ratios spanning a wide range. *Pleurotus ostreatus* shows a high strength-to-density ratio of 0.0958 MPa/(kg/m^3). This makes it a promising candidate for applications demanding high strength-to-density requirements. *Ganoderma lucidum* and *Oudemansiella radicata*, on the other hand, demonstrate relatively lower specific strength ratios. This suggests that these species may have limitations in delivering strength in proportion to their density. Compared with other traditional materials, the specific strength ratio of *Pleurotus ostreatus* is higher than the specific strength ratio of clear softwood, standard clay brick, and plywood. This means that using *Pleurotus ostreatus* to grow MBCs may be a potential alternative to traditional construction materials in civil engineering.

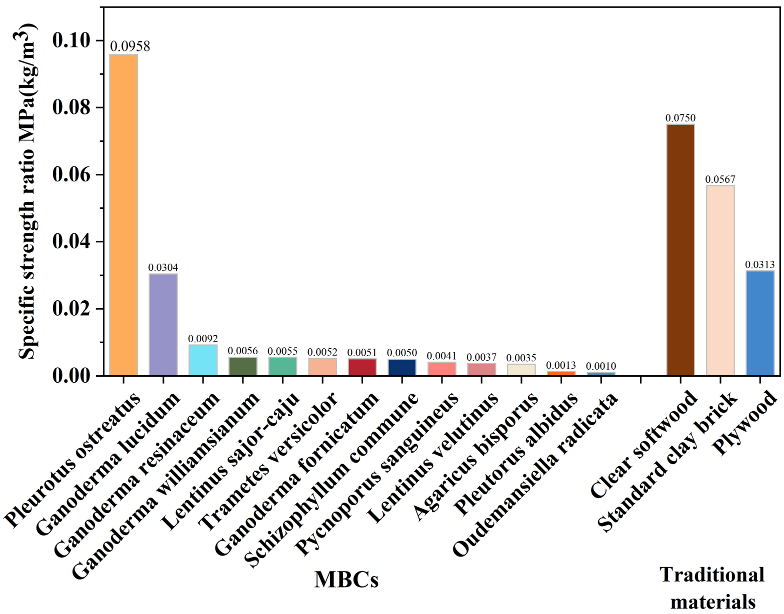

Figure 6. The specific strength ratio of different MBCs and traditional materials.

4.2. Strength-to-Weight Ratio

The strength-to-weight ratio is used to compare the strength properties of different materials, taking into account their weight. A higher strength-to-weight ratio means that the material is capable of providing more strength for a given mass. By utilising MBCs with a higher strength-to-weight ratio, engineers and designers can achieve lightweight structures without compromising strength and structural integrity. This provides the opportunity for innovative designs where the weight of the material can be minimised while meeting the necessary strength requirements. Applications such as lightweight panels, structural components and load-bearing elements can benefit from MBCs with a favourable strength-to-weight ratio.

Trametes versicolor demonstrates a maximum strength-to-weight ratio of 0.3188 MPa/g, making it a potentially valuable material for non-structural applications in civil engineering (Figure 7), compared to standard clay brick, clear softwood, and plywood. Comparatively, other fungal species, such as *Pycnoporus sanguineus*, *Pleurotus ostreatus*, *Ganoderma lucidum*, and *Lentinus squarrosulus* exhibit much lower values ranging from 0.0037 MPa/g to 0.0139 MPa/g. While their strength values might be decent, their weight relative to their strength could limit their performance in applications where weight reduction is essential.

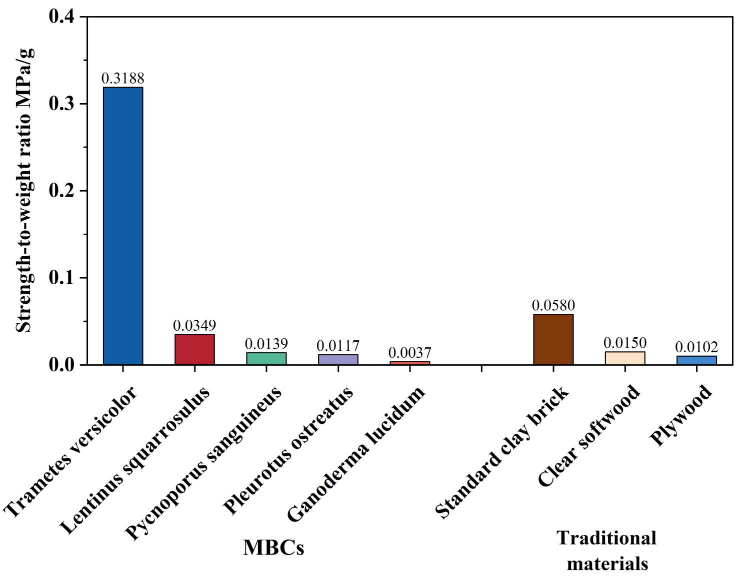

Figure 7. The strength-to-weight ratio of different MBCs and traditional materials.

4.3. Specific Modulus

The specific modulus is the ratio between the modulus of elasticity of a material and its density. A higher specific modulus indicates a material with higher stiffness or elastic properties for a given mass.

The specific modulus values of several fungal species and traditional materials are presented in Figure 8. *Pleurotus ostreatus* and *Trametes multicolor* emerge as prominent species in this aspect. *Pleurotus ostreatus*, with a maximum specific modulus value of 0.2744 MPa/(kg/m^3), would be suitable for applications demanding high rigidity and stability. *Trametes multicolor* also displays reasonable specific modulus values, although slightly lower than *Pleurotus ostreatus*. The specific modulus of *Trametes versicolor* and *Ganoderma lucidum* are 0.0121 MPa/(kg/m^3) and 0.0304 MPa/(kg/m^3), respectively. These are some of the lowest values observed among the fungal species studied. However, compared with traditional materials, the currently studied of MBCs still provide no substitute for these three traditional materials based on specific modulus. Further research is still needed to find potentially high specific modulus MBCs to replace traditional materials.

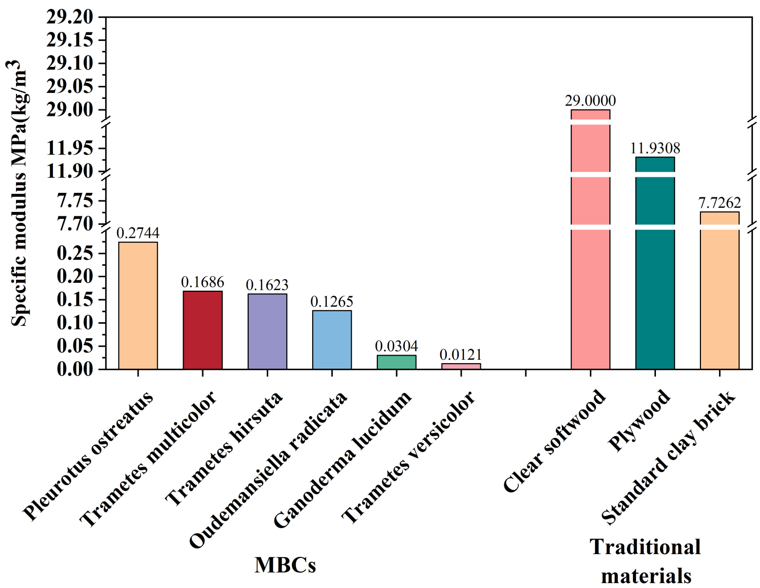

Figure 8. The specific modulus of different MBCs and traditional materials.

5. A Fuzzy Comprehensive Evaluation for MBCs Ranking

In this section, a case study is presented, utilising fuzzy comprehensive evaluation (FCE), to systematically rank five distinct MBCs for non-primary structure members. In this context, the comprehensive performance evaluation of mycelium composites was conducted as potential materials for secondary structural members, encompassing both outer-frame and inner-frame configurations. This evaluation offers insights into the suitability and prospects of each mycelium composite for façade construction applications. The key properties of MBCs, including density, water absorption, tensile strength, flexural strength, and production time were assessed and analysed. Additionally, the weight proportions of these evaluation factors in the context of façade applications were evaluated using the analytic hierarchy process (AHP).

5.1. Weight Vector Determination

The analytic hierarchy process (AHP) enables the conduct of complex pairwise cross-comparisons. The significance of each variable can be systematically determined by applying a numerical scale for comparison. The weight vector required to evaluate various MBCs manufactured with different fungi can be obtained using the procedures below. In the initial phase of variable determination, five variables (density, water absorption, tensile strength, flexural strength, and manufacturing period) were collected from prior research for the purpose of comparing the properties of different MBCs. In the second phase, matrices for pairwise comparisons were created. The pairwise relationships between each pair of variables for both conditions were defined according to studies conducted by Chen [98], Patnaik et al. [99], and Lee et al. [100]. The relative importance of each variable was subsequently determined by comparing it to its corresponding variable using the Saaty linear scale and then converting the results into numerical data. The pairwise comparison matrix is shown in Table 1.

Table 1. Pairwise comparison matrix.

Matrix Framework		**Satisfaction with Product Quality**				**Service Level**
		Density (D)	**Water Absorption (WA)**	**Tensile Strength (TS)**	**Flexural Strength (FS)**	**Manufacturing Period (MP)**
Satisfaction with product quality	Density (D)	1	D/WA	D/TS	D/FS	D/MP
	Water absorption (WA)	WA/D	1	WA/TS	WA/FS	WA/MP
	Tensile strength (TS)	TS/D	TS/WA	1	TS/FS	TS/MP
	Flexural strength (FS)	FS/D	FS/WA	FS/TS	1	FS/MP
Service level	Manufacturing period (MP)	MP/D	MP/WA	MP/TS	MP/FS	1

The eigenvector (ν) and principal eigenvalue (λ_{max}) were determined to be (0.436, 0.143, 2.599, 0.949, 0.873) and 5.276, respectively. Subsequently, further transformations led to the calculation of weight proportions for each criterion: 8.772% for density, 2.857% for water absorption, 51.978% for tensile strength, 18.979% for flexural strength, and 17.464% for manufacturing time. These results highlight the importance of material choice for non-primary structure members.

After calculating the weight vector, it is necessary to assess the consistency of the resultant matrix using the consistency ratio (CR), as shown in Equation (1). If the CR value exceeds the threshold of 0.1, it indicates the possibility of subjective judgment-based errors during matrix construction. Otherwise, the result is considered reasonable [50]. The consistency index (*CI*) can be calculated using Equation (2), while the average random index (*RI*) was determined to be 1.12 [51]. With a calculated CR value of 0.062, which is below the threshold of 0.1, it can be concluded that the matrix's consistency was adequate.

$$\mathrm{CR} = \frac{CI}{RI} = \frac{\sum_{i=1}^{n} \frac{\left(A\vec{\omega}\right)_i}{n\omega_i} - n}{RI(n-1)} \leq 0.1 \tag{1}$$

where A is the formed pairwise matrix, ω_i is the weight vector, n is the number of variables, RI is an average random index, and CI is the consistency index.

$$CI = \frac{\lambda_{max} - n}{n - 1} = 0.069 \tag{2}$$

where n is the size of the matrix.

5.2. Fuzzy Comprehensive Evaluation

The FCE (fuzzy comprehensive evaluation) method was used to establish a systematic ranking system for the selection of mycelium composites as secondary structural members in façade construction. The evaluative variables or factors (U) included density, water absorption, tensile strength, flexural strength, and manufacturing periods. Each criterion was assigned assessment levels (V) on a predetermined scale, ranging from outstanding to poor. Appendix C provides information about the specific ranking criteria and their corresponding evaluation levels. By integrating both mechanical properties and manufacturing time into the material selection process, architects and designers can make well-informed decisions for their projects, achieving the optimal balance between performance and time. *Trametes multicolor*, *Pleurotus ostreatus*, *Ganoderma williamsianum*, *Lentinus sajor-caju*, and *Schizophyllum commune* mycelium composites were investigated for their potential application as façade construction materials. Based on the findings shown in Figure 9, *Pleurotus ostreatus* emerged as the most promising fungus for the production of mycelium composites used in façades, achieving a reasonable balance between material performance and production time. In this investigation, however, the range for each variable is unknown due to the lack of available data. Future research can enhance the robustness of these findings by increasing the sample size.

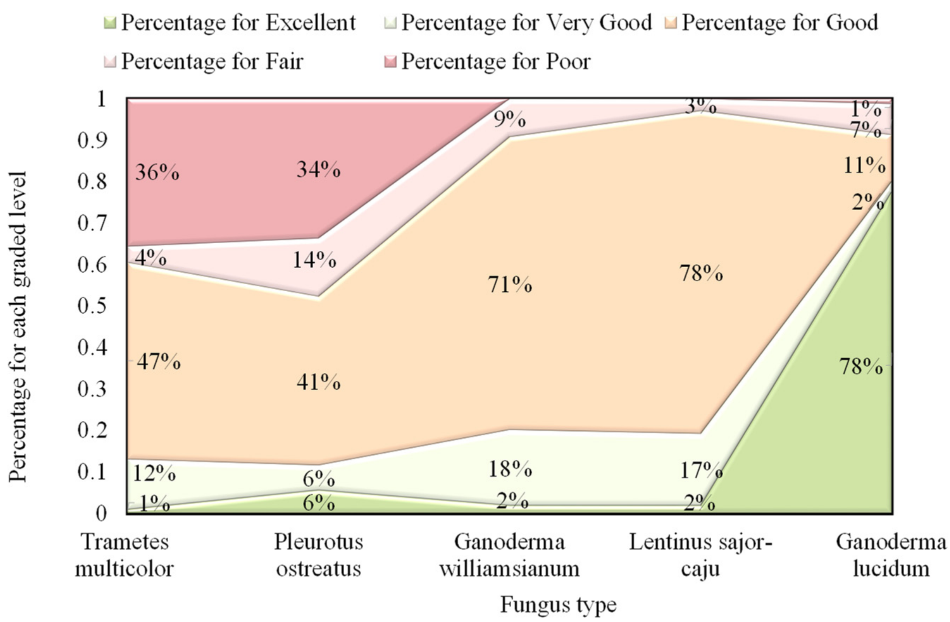

Figure 9. Ranking for mycelium composites manufactured with five different fungi.

6. Future Outlook

The majority of MBCs in the literature have been cultured in moulds. However, the adoption of 3D printing holds the potential to advance the production of complex geometries and facilitate the utilisation of novel materials. This technology enables the creation of complex shapes, often characterised by augmented surface area [52]. The utilisation of 3D printing could lead to increased oxygen exposure for mycelium, potentially enhancing its growth rate and production efficiency.

Several studies have tried to use 3D printing for the production of MBCs. To find a suitable solution, psyllium husk powder was added to the Ecovative mixture as a substrate [89]. To create an extrudable paste or a combination with specified properties, water and a gelling agent need to be added to the colonizing-mycelium mixture [101]. In several trials, psyllium husk powder was utilised as gelling agent [102]. In another study, the use of psyllium husk powder was proposed as a means to maintain moisture in the mycelium mixture and to serve as a gel for binding the 3D printed layers together [65]. To enable 3D printing of the mycelium without disinfection, an experiment was conducted involving the inoculation of a mixture comprised of soil, glycerol, xanthan gum, molasses, guar gum, and wet hay with the *Pleurotus* fungus [90]. This offered the chance to use the myco-techniques for ecological restoration using fungi. In addition, mycelium was mixed with clay to achieve a composition suitable for 3D printing, resulting in graded MBCs [54]. Different ratios of gum were used to enable the printable mixture to undergo bio-welding after extrusion [55]. Alternative rheological materials, like alginate, were also used to create a stabilised extrudable paste using novel species such as *Fomes fomentarius* [92]. Nonetheless, there are limitations associated with 3D printing mycelium. The main limitations are substrate clogging during extrusion, poor print quality, challenges in halting the growth process, and susceptibility to microbial contamination in the final product [93]. Despite these challenges, these endeavours hold promising potential, and there is a possibility of scaling up the 3D printing of mycelium-bound building elements for further testing.

The concept of 4D printing builds upon 3D printing by introducing dynamic factors like water, light, heat, electric current, magnetic fields, and acidic and alkaline environments [93]. After 3D printing the MBCs panels, mycelial spores are scattered on their designated geometric surfaces. By controlling the relative humidity and temperature, it may be possible to adjust the mycelium growth rate and thus control its overall composite performance. The incorporation of environmental factors within multidimensional printing offers a means to precisely control mycelium growth during the preparation of future mycelium composites, facilitating the attainment of desired material properties.

As research and development continues to advance, a number of innovative manufacturing methods have emerged in the field of bio-based materials. Some of these methods have been successfully applied in other bio-based composites but have not yet been fully explored in the production of MBCs. These methods could potentially further improve the properties and expand the applications of MBCs, making them become more attractive and widely used biomaterials.

A promising manufacturing method is the incorporation of natural fibres or reinforcements into the MBCs. This method is already widely used in Natural Fibre-Reinforced Polymers (NFRP) [94]. Common natural fibres include hemp, flax, and bamboo. These natural fibres are combined with polymeric matrices such as thermoplastic or thermosetting resins to form composites with high mechanical properties. The combination of these natural fibres into the substrate of MBCs is expected to improve the mechanical strength, durability and flexibility of MBCs. For example, in the construction sector, bamboo fibres may be combined with a mycelium substrate to create construction panels with high strength and toughness. These panels may be used in the construction of structures such as walls, floors and roofs or outdoor structures, providing a more environmentally friendly and sustainable alternative with high weather resistance and strength [94].

Another promising technology that has been successfully explored in other bio-based composites is the integration of additives or nanoparticles into composite materials. These additives or nanoparticles have specific physical and chemical properties that can impart specific functions to MBCs, such as the electrical conductivity of graphene [95] and the enhanced stability of clay nanoparticles [97]. Adding flame retardants to the substrate of MBCs may improve its fire-resistant properties, making it safer and more reliable in construction. For example, in the manufacture of firewalls, insulation panels and building structures, the addition of aluminium oxide nanoparticles may significantly improve the fire resistance of MBCs and protect buildings from fire. Meanwhile, the combination of graphene nanoparticles into MBCs substrates can improve the material's electrical conductivity, making it an option for the manufacture of smart building materials and wearable sensors.

Lastly, a promising manufacturing method involves the production of mycelium using advanced microbial fermentation techniques. Unlike conventional MBCs production, which is often time and resource-intensive, mycelium can be efficiently manufactured using microbial fermentation technology. Through microbial fermentation technology, it may be possible to create MBCs materials with complex porous structures, providing more functionality and innovative designs for buildings. For example, by controlling the growth conditions of mycelial networks and mould design, it may be possible to create building materials, such as acoustic sound insulation panels, air filters, and eco-bricks with specific shapes and pore structures.

7. Conclusions

Mycelium-bound composites offer numerous advantages, such as low density, thermal and acoustic performance, cost-effectiveness, and a reduced carbon footprint. This research explored the potential of mycelium-bound composites as sustainable alternatives to traditional materials, specifically as non-primary structural members. The density of the composites plays a crucial role in their structural integrity and weight. Different fungal and substrate species, along with factors like moisture content and temperature, influence the density of the composites. Certain substrates, including Chinese hyacinth sawdust and lavender straw, result in higher densities compared to others. Another important property is water absorption capacity, which varies depending on the substrate and fungal species. Composites manufactured on dense substrates exhibit low water absorption, while *Fucus* species and *Ganoderma* species show different water uptake capacities on various substrates. The composition of the substrate, particularly the presence of lignin, cellulose, and hemicellulose, affects the water uptake capacity of mycelium-bound composites. Overall, these findings demonstrate the potential and versatility of mycelium-bound composites in sustainable construction applications. Mycelium's capacity to absorb water can also be affected by environmental factors and the fungus's growth stage.

This paper also examined the mechanical properties of MBCs, including the compressive strength, flexural strength, tensile strength, and Young's modulus of various fungal species. Researchers are continuously exploring ways to improve the mechanical properties of MBCs to broaden their application in different industries. Based on the available research, it is evident that MBCs cannot currently replace traditional building materials such as clay brick, clear softwood, and plywood. However, it is worth noting that the mechanical properties of MBCs can be enhanced through various methods, including the addition of reinforcing materials such as natural fibres or adjusting growth conditions to promote a denser mycelial network. The significant factors to consider when applying different MBCs in structural applications were determined and compared for different MBCs. Among the fungal species evaluated, *Pleurotus ostreatus* demonstrates remarkable specific strength and the highest specific modulus, making it promising for lightweight yet strong structures, particularly in applications that require high stiffness. *Trametes versicolor*, with its significant strength-to-weight ratio, has potential in applications where strength and weight efficiency are prioritised.

This study also included a case study that employs fuzzy comprehensive evaluation to assess the suitability of MBCs for façade construction. The comprehensive evaluation method is effective for the comparison and ranking of different MBCs resulting in material selection guide. By comparing MBCs made with *Trametes multicolour*, *Ganoderma williamsianum*, *Lentinus sajor-caju*, and *Schizophyllum commune*, it was found that MBCs utilising *Pleurotus ostreatus* demonstrate the most promising characteristics for façades, achieving a desirable balance between material performance and production time. Moreover, the future advancement of manufacturing techniques for MBCs construction components, including the potential implementation of 3D printing and the incorporation of additives to enhance MBCs strength, were examined. These evaluations provide valuable insights to enhance the productivity of MBCs and underscore their potential applications in civil engineering [103–115].

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Appendix A

Table A1. Comparison of different physical properties of engineered MBCs under different manufacturing conditions.

Physical Properties			
Fungal Species	**Substrates**	**Values**	**Author**
Density (kg/m^3)			
Trametes versicolor	Wheat straw	122.1	Elsacker et al. [35]
	Spent mushroom	195.2	Schritt, Vidi and Pleissner [53]
	Rice hull	193.0	Teixeira et al. [116]
	Hemp shives	134.0	Jones et al. [87]
	Pine wood	159.5	Elsacker et al. [35]
	Hemp hurds	98.4	Elsacker et al. [35]
	Hardwood chips	179.0	Jones et al. [87]
	Flax	137.5	Elsacker et al. [35]
	Beech sawdust	200.1	Schritt, Vidi and Pleissner [53]
Trametes multicolor	Rapeseed straw	350.0	Appels et al. [43]
	Rapeseed straw	100.0	Appels et al. [43]
	Beech sawdust	170.0	Appels et al. [43]
Trametes hirsuta	Pine wood shaving	260.0	Kuribayashi et al. [117]
Trametes species	Vine wood chip	210.0	Attias, Danai, Tarazi, et al. [56]
	Apple wood chip	200.0	Attias, Danai, Tarazi, et al. [56]
Pycnoporus sanguineus	Pine sawdust	320.0	Bruscato et al. [118]
	Coconut powder	240.0	Santos et al. [119]

Table A1. *Cont.*

Physical Properties			
Fungal Species	**Substrates**	**Values**	**Author**
	Density (kg/m^3)		
Pleurotus ostreatus	Straw	277.0	Ghazvinian et al. [51]
	Rice husk	437.0	Nashiruddin et al. [38]
	Rapeseed straw	390.0	Appels et al. [43]
	Rapeseed straw	240.0	Appels et al. [43]
	Rapeseed straw	130.0	Appels et al. [43]
	Rapeseed cake	49.0	Tacer-Caba et al. [97]
	Pine wood shaving	290.0	Kuribayashi et al. [117]
	Oat husk	38.0	Tacer-Caba et al. [97]
	Cotton stalk	325.0	Gou et al. [49]
	100% sawdust	55.0	Ghazvinian et al. [51]
	90% sawdust/10% wheat bran	49.0	Ghazvinian et al. [51]
	100% straw	28.0	Ghazvinian et al. [51]
	90% straw/10% wheat bran	19.0	Ghazvinian et al. [51]
	50% sawdust/50% straw	25.0	Ghazvinian et al. [51]
	45% sawdust/45% straw/ 10% wheat bran	23.0	Ghazvinian et al. [51]
	Beech sawdust	26.0	Vašatko et al. [78]
	Bleached cellulose pulp	34.0	Vašatko et al. [78]
	Beech sawdust/soy silk fibres	24.0	Vašatko et al. [78]
	Shredded cardboard	42.0	Vašatko et al. [78]
	Sand/beach sawdust	37.0	Vašatko et al. [78]
	Cotton fibres	22.0	Vašatko et al. [78]
	Rice straw	27.0	Peng et al. [57]
	Bagasse	30.0	Peng et al. [57]
	Coir-pith	30.0	Peng et al. [57]
	Sawdust	34.0	Peng et al. [57]
	Corn straw	25.0	Peng et al. [57]
	Cotton	350.0	Appels et al. [43]
	Cotton	240.0	Appels et al. [43]
	Cotton	130.0	Appels et al. [43]
Pleutorus albidus	Pine sawdust	300.0	Bruscato et al. [118]
Pleurotus species	Wheat straw	183.8	López Nava et al. [120]
Oudemansiella radicata	Cotton stalk	317.0	Gou et al. [49]
Lentinus velutinus	Pine sawdust	350.0	Bruscato et al. [118]
Ganoderma resinaceum	Rose flowers	462.0	Angelova et al. [58]
	Miscanthus fibre	200.0	Dias, Jayasinghe and Waldmann [44]
	Lavender straw	347.0	Angelova et al. [58]
	Beechwood sawdust	143.0	Elsacker, Søndergaard, et al. [55]

Table A1. *Cont.*

Physical Properties			
Fungal Species	**Substrates**	**Values**	**Author**
Density (kg/m^3)			
Ganoderma lucidum	Spent mushroom	183.2	Schritt, Vidi and Pleissner [53]
	Rapeseed cake	41.0	Tacer-Caba et al. [97]
	Oat husk	25.0	Tacer-Caba et al. [97]
	Chinese albizia sawdust	954.0	Chan et al. [42]
	Chinese albizia sawdust	130.0	Chan et al. [42]
	Beech sawdust	205.3	Schritt, Vidi and Pleissner [53]
	Beech sawdust	25.0	Vašatko et al. [78]
Ganoderma species	Vine wood chip	210.0	Attias, Danai, Tarazi, et al. [56]
	Apple wood chip	220.0	Attias, Danai, Tarazi, et al. [56]
Coriolus species	Vine wood chip	180.0	Attias, Danai, Tarazi, et al. [56]
	Apple wood chip	210.0	Attias, Danai, Tarazi, et al. [56]
Ganoderma fornicatum	Sawdust	337.2	Aiduang et al. [50]
	Corn husk	232.1	Aiduang et al. [50]
	Rice straw	219.4	Aiduang et al. [50]
Ganoderma williamsianum	Sawdust	331.4	Aiduang et al. [50]
	Corn husk	239.5	Aiduang et al. [50]
	Rice straw	221.1	Aiduang et al. [50]
Lentinus sajor-caju	Sawdust	340.3	Aiduang et al. [50]
	Corn husk	241.0	Aiduang et al. [50]
	Rice straw	222.8	Aiduang et al. [50]
Schizophyllum commune	Sawdust	318.6	Aiduang et al. [50]
	Corn husk	220.7	Aiduang et al. [50]
	Rice straw	198.8	Aiduang et al. [50]
Agaricus bisporus	Rapeseed cake	58.0	Tacer-Caba et al. [97]
	Oat husk	36.0	Tacer-Caba et al. [97]
Water absorption (%)			
Trametes versicolor	Wheat straw	26.8	Elsacker et al. [35]
	Hemp hurds	24.4	Elsacker et al. [35]
	Flax	30.3	Elsacker et al. [35]
	Hardwood chips	400	Jones et al. [87]
	Hemp shives	560	Jones et al. [87]
Trametes multicolor	Rapeseed straw	246	Appels et al. [43]
	Rapeseed straw	436	Appels et al. [43]
	Beech sawdust	43	Appels et al. [43]
Trametes hirsuta	Pine wood shaving	200	Kuribayashi et al. [117]
Trametes species	Vine wood chip	190	Attias, Danai, Tarazi, et al. [56]
	Apple wood chip	200	Attias, Danai, Tarazi, et al. [56]

Table A1. *Cont.*

Physical Properties			
Fungal Species	**Substrates**	**Values**	**Author**
Density (kg/m^3)			
Pleurotus ostreatus	Rice straw	131	Ghazvinian et al. [51]
	Sawdust	140	Lee and Choi [54]
	Rapeseed straw	239	Appels et al. [43]
	Rapeseed straw	262	Appels et al. [43]
	Rapeseed straw	279	Appels et al. [43]
	Pine wood shaving	200	Kuribayashi et al. [117]
	Oak wood chip	76	Lee and Choi [54]
	Lacquer wood chip	135	Lee and Choi [54]
	Hemp	159	Lee and Choi [54]
	Cotton stalk	168.1	Gou et al. [49]
	Beech sawdust	29	Appels et al. [78]
	Cotton	281	Appels et al. [43]
	Cotton	238	Appels et al. [43]
	Cotton	508	Appels et al. [43]
Pleurotus species	Wheat straw	268.4	López Nava et al. [120]
Oudemansiella radicata	Cotton stalk	162.4	Gou et al. [49]
Lentinula edodes	Peach palm sheath	351	de Lima et al. [59]
Ganoderma resinaceum	Rose flowers	43.9	Angelova et al. [58]
	Lavender straw	114.6	Angelova et al. [58]
	Miscanthus fibre	125	Dias, Jayasinghe and Waldmann [44]
Ganoderma lucidum	Beech sawdust	6	Vašatko et al. [78]
Ganoderma species	Vine wood chip	180	Attias, Danai, Tarazi, et al. [56]
	Apple wood chip	200	Attias, Danai, Tarazi, et al. [56]
Coriolus species	Vine wood chip	290	Attias, Danai, Tarazi, et al. [56]
	Apple wood chip	240	Attias, Danai, Tarazi, et al. [56]
Ganoderma fornicatum	Sawdust	100	Aiduang et al. [50]
	Corn husk	121	Aiduang et al. [50]
	Rice straw	149	Aiduang et al. [50]
Ganoderma williamsianum	Sawdust	90	Aiduang et al. [50]
	Corn husk	114	Aiduang et al. [50]
	Rice straw	90	Aiduang et al. [50]
Lentinus sajor-caju	Sawdust	84	Aiduang et al. [50]
	Corn husk	90	Aiduang et al. [50]
	Rice straw	156	Aiduang et al. [50]
Schizophyllum commune	Sawdust	120	Aiduang et al. [50]
	Corn husk	140	Aiduang et al. [50]
	Rice straw	188	Aiduang et al. [50]
Lentinus squarrosulus	Rice husk	229.1	Ly and Jitjak [60]
	Rice straw	229.1	Ly and Jitjak [60]
	Coconut husk	609	Ly and Jitjak [60]

Appendix B

Table A2. Comparison of different mechanical properties of engineered MBCs under different manufacturing conditions.

Mechanical Properties			
Fungal Species	**Substrates**	**Values**	**Author**
	Compression strength (MPa)		
Trametes versicolor	Rice hull	0.05	Teixeira et al. [116]
	Pine wood	0.14	Elsacker et al. [35]
	Hemp hurds	0.51	Elsacker et al. [35]
	Flax	0.31	Elsacker et al. [35]
Pycnoporus sanguineus	Pine sawdust	1.30	Bruscato et al. [118]
	Coconut powder	0.19	Santos et al. [119]
Pleurotus ostreatus	Straw	0.07	Ghazvinian et al. [51]
	Sawdust	1.00	Ghazvinian et al. [51]
	Rice husk	1.35	Nashiruddin et al. [38]
	Rapeseed cake	0.28	Tacer-Caba et al. [97]
	Oat husk	0.03	Tacer-Caba et al. [97]
	Cotton stalk	0.13	Gou et al. [49]
	100% sawdust	0.15	Ghazvinian et al. [51]
	90% sawdust/10% wheat bran	0.19	Ghazvinian et al. [51]
	100% straw	0.02	Ghazvinian et al. [51]
	90% straw/10% wheat bran	0.03	Ghazvinian et al. [51]
	50% sawdust/50% straw	0.03	Ghazvinian et al. [51]
	45% sawdust/45% straw/ 10% wheat Bran	0.31	Ghazvinian et al. [51]
	Beech sawdust	2.49	Vašatko et al. [78]
	Bleached cellulose pulp	0.51	Vašatko et al. [78]
	Beech sawdust/soy silk fibres	1.99	Vašatko et al. [78]
	Shredded cardboard	2.65	Vašatko et al. [78]
	Sand/beach sawdust	0.35	Vašatko et al. [78]
	Cotton fibres	0.80	Vašatko et al. [78]
	Rice straw	0.30	Peng et al. [57]
	Bagasse	0.34	Peng et al. [57]
	Coir-pith	0.34	Peng et al. [57]
	Sawdust	0.46	Peng et al. [57]
	Corn straw	0.27	Peng et al. [57]
Pleutorus albidus	Pine sawdust	0.40	Bruscato et al. [118]
Pleurotus species	Wheat straw	0.04	López Nava et al. [120]
Oudemansiella radicata	Cotton stalk	0.09	Gou et al. [49]
Lentinus velutinus	Pine sawdust	1.30	Bruscato et al. [118]
Lentinula edodes	Peach palm sheath	0.22	de Lima et al. [59]
	Coconut powder	0.06	Angelova et al. [119]

Table A2. *Cont.*

Mechanical Properties			
Fungal Species	**Substrates**	**Values**	**Author**
Compression strength (MPa)			
Ganoderma resinaceum	Rose flowers	1.03	Angelova et al. [58]
	Lavender straw	0.72	Angelova et al. [58]
	Miscanthus fibre	1.80	Dias, Jayasinghe and Waldmann [44]
	Beechwood sawdust	1.32	Elsacker, Søndergaard, et al. [55]
Ganoderma lucidum	Rapeseed cake	0.28	Tacer-Caba et al. [97]
	Oat husk	0.13	Tacer-Caba et al. [97]
	Chinese albizia sawdust	4.44	Chan et al. [42]
	Chinese albizia sawdust	3.36	Chan et al. [42]
	Beech sawdust	0.76	Vašatko et al. [78]
Fomes fomentarius	Rapeseed straw	0.30	Pohl et al. [121]
	Hemp shives	0.20	Pohl et al. [121]
Ganoderma fornicatum	Sawdust	1.71	Aiduang et al. [50]
	Corn husk	0.59	Aiduang et al. [50]
	Rice straw	0.33	Aiduang et al. [50]
Ganoderma williamsianum	Sawdust	1.85	Aiduang et al. [50]
	Corn husk	0.62	Aiduang et al. [50]
	Rice straw	0.36	Aiduang et al. [50]
Lentinus sajor-caju	Sawdust	1.87	Aiduang et al. [50]
	Corn husk	0.62	Aiduang et al. [50]
	Rice straw	0.33	Aiduang et al. [50]
Schizophyllum commune	Sawdust	1.59	Aiduang et al. [50]
	Corn husk	0.58	Aiduang et al. [50]
	Rice straw	0.25	Aiduang et al. [50]
Lentinus squarrosulus	Rice husk	0.46	Ly and Jitjak [60]
	Rice straw	0.54	Ly and Jitjak [60]
	Coconut husk	0.47	Ly and Jitjak [60]
Agaricus bisporus	Rapeseed cake	0.20	Tacer-Caba et al. [97]
	Oat husk	0.06	Tacer-Caba et al. [97]
Flexural strength (MPa)			
Trametes multicolor	Rapeseed straw	0.86	Appels et al. [43]
	Rapeseed straw	0.22	Appels et al. [43]
	Beech sawdust	0.29	Appels et al. [43]
Pleurotus ostreatus	Rapeseed straw	0.87	Appels et al. [43]
	Rapeseed straw	0.21	Appels et al. [43]
	Rapeseed straw	0.06	Appels et al. [43]
	Rubber sawdust	3.91	Shakir et al. [61]
	Pine wood shaving	0.94	Kuribayashi et al. [117]
	Beech sawdust	0.11	Vašatko et al. [78]

Table A2. *Cont.*

Mechanical Properties			
Fungal Species	**Substrates**	**Values**	**Author**
Compression strength (MPa)			
Pleurotus ostreatus	Bleachedd cellulose pulp	0.35	Vašatko et al. [78]
	Shredded cardboard	0.21	Vašatko et al. [78]
	Sand/beach sawdust	0.40	Vašatko et al. [78]
	Rice straw	0.16	Peng et al. [57]
	Bagasse	0.54	Peng et al. [57]
	Coir-pith	0.32	Peng et al. [57]
	Sawdust	0.30	Peng et al. [57]
	Corn straw	0.30	Peng et al. [57]
	Cotton	0.62	Appels et al. [43]
	Cotton	0.24	Appels et al. [43]
	Cotton	0.05	Appels et al. [43]
Ganoderma resinaceum	Beechwood sawdust	2.54	Elsacker, Søndergaard, et al. [55]
Ganoderma lucidum	Chinese albizia sawdust	2.68	Chan et al. [42]
	Chinese albizia sawdust	2.53	Chan et al. [42]
	Beech sawdust	0.09	Vašatko et al. [78]
Ganoderma fornicatum	Sawdust	0.07	Aiduang et al. [50]
	Corn husk	0.19	Aiduang et al. [50]
	Rice straw	0.10	Aiduang et al. [50]
Ganoderma williamsianum	Sawdust	1.85	Aiduang et al. [50]
	Corn husk	0.62	Aiduang et al. [50]
	Rice straw	0.36	Aiduang et al. [50]
Lentinus sajor-caju	Sawdust	1.87	Aiduang et al. [50]
	Corn husk	0.62	Aiduang et al. [50]
	Rice straw	0.33	Aiduang et al. [50]
Schizophyllum commune	Sawdust	1.59	Aiduang et al. [50]
	Corn husk	0.58	Aiduang et al. [50]
	Rice straw	0.25	Aiduang et al. [50]
Lentinus squarrosulus	Rice husk	0.46	Ly and Jitjak [60]
	Rice straw	0.54	Ly and Jitjak [60]
	Coconut husk	0.47	Ly and Jitjak [60]
Agaricus bisporus	Rapeseed cake	0.20	Tacer-Caba et al. [97]
	Oat husk	0.06	Tacer-Caba et al. [97]
Tensile strength (MPa)			
Trametes multicolor	Rapeseed straw	0.15	Appels et al. [43]
	Rapeseed straw	0.04	Appels et al. [43]
	Beech sawdust	0.05	Appels et al. [43]

Table A2. *Cont.*

Mechanical Properties			
Fungal Species	**Substrates**	**Values**	**Author**
	Compression strength (MPa)		
Pleurotus ostreatus	Rapeseed straw	0.24	Appels et al. [43]
	Rapeseed straw	0.03	Appels et al. [43]
	Rapeseed straw	0.01	Appels et al. [43]
	Cotton	0.13	Appels et al. [43]
	Cotton	0.03	Appels et al. [43]
Pleurotus species	Wheat straw	0.05	López Nava et al. [120]
Ganoderma lucidum	Chinese albizia sawdust	1.55	Chan et al. [42]
	Chinese albizia sawdust	1.53	Chan et al. [42]
Ganoderma fornicatum	Sawdust	0.34	Aiduang et al. [50]
	Corn husk	0.63	Aiduang et al. [50]
	Rice straw	0.37	Aiduang et al. [50]
Ganoderma williamsianum	Sawdust	0.42	Aiduang et al. [50]
	Corn husk	0.75	Aiduang et al. [50]
	Rice straw	0.46	Aiduang et al. [50]
Lentinus sajor-caju	Sawdust	0.44	Aiduang et al. [50]
	Corn husk	0.87	Aiduang et al. [50]
	Rice straw	0.45	Aiduang et al. [50]
Schizophyllum commune	Sawdust	0.20	Aiduang et al. [50]
	Corn husk	0.63	Aiduang et al. [50]
	Rice straw	0.35	Aiduang et al. [50]
	Young's modulus (MPa)		
Trametes versicolor	Pine wood	15	Elsacker et al. [35]
	Hemp hurds	1.19	Elsacker et al. [35]
	Flax	1.32	Elsacker et al. [35]
Trametes multicolor	Rapeseed straw	59	Appels et al. [43]
	Rapeseed straw	4	Appels et al. [43]
	Beech sawdust	13	Appels et al. [43]
Trametes hirsuta	Pine wood shaving	42.21	Kuribayashi et al. [117]
Pleurotus ostreatus	Rapeseed straw	97	Appels et al. [43]
	Rapeseed straw	9	Appels et al. [43]
	Rapeseed straw	2	Appels et al. [43]
	Pine wood shaving	79.57	Kuribayashi et al. [117]
	Cotton stalk	60	Gou et al. [49]
	Cotton	35	Appels et al. [43]
	Cotton	6	Appels et al. [43]
	Cotton	1	Appels et al. [43]

Table A2. *Cont.*

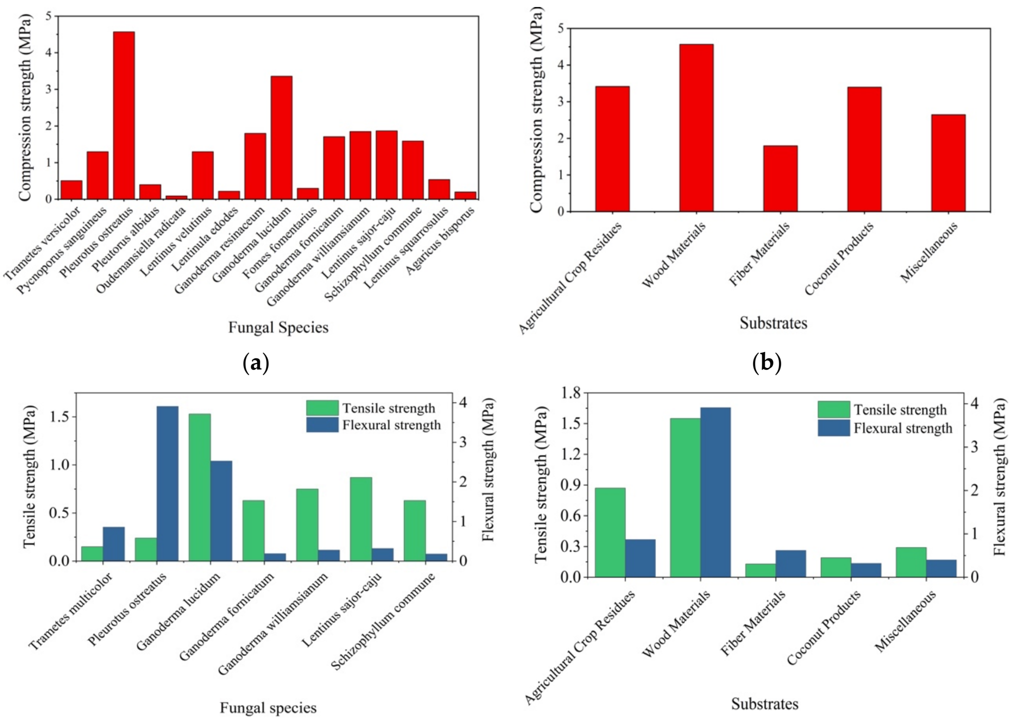
Mechanical Properties			
Fungal Species	**Substrates**	**Values**	**Author**
	Compression strength (MPa)		
Oudemansiella radicata	Cotton stalk	40.10	Gou et al. [49]
Lentinula edodes	Peach palm sheath	15	de Lima et al. [59]
Ganoderma lucidum	Oat husk	76	Tacer-Caba et al. [97]
Fomes fomentarius	Rapeseed straw	54	Pohl et al. [121]
	Hemp shives	43	Pohl et al. [121]

Appendix C

Table A3. Evaluation scale used in FCE.

Level	Excellent	Very Good	Good	Fair	Poor
Density, D (kg/m^3)	D < 100	100 ≤ D < 200	200 ≤ D < 300	300 ≤ D < 500	D ≥ 500
Water absorption, WA (%)	WA < 100	100 ≤ WA < 150	150 ≤ WA < 200	200 ≤ WA < 300	WA ≥ 300
Tensile strength, TS (MPa)	TS > 1	0.5 < TS ≤ 1	0.1 < TS ≤ 0.5	0.05 < TS ≤ 0.1	TS ≤ 0.05
Flexural strength, FS (MPa)	FS > 1	0.5 < FS ≤ 1	0.1 < FS ≤ 0.5	0.05 < FS ≤ 0.1	FS ≤ 0.05
Manufacturing period, MP (days)	MT < 15	15 ≤ MT < 20	20 ≤ MT < 25	25 ≤ MT < 30	MT ≥ 30

Appendix D



(c) (d)

Figure A1. The maximum: (**a**) compressive strength value of different fungal species, (**b**) compressive strength value of different substrates, (**c**) flexural strength and tensile strength value of different fungal species, (**d**) flexural strength and tensile strength value of different substrates.

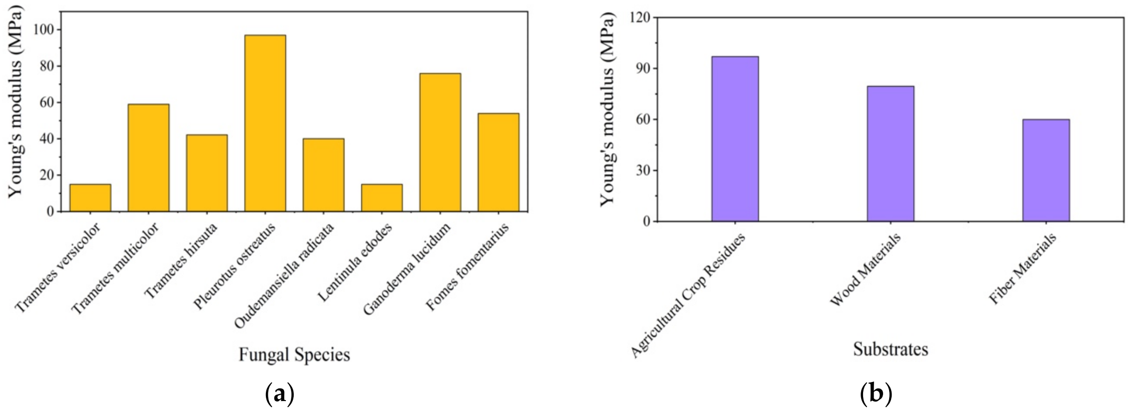


Figure A2. Maximum Young's modulus value of different (**a**) fungal species and (**b**) substrates.

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