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Review

Natural Fiber-Reinforced Mycelium Composite for Innovative and Sustainable Construction Materials

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Abstract: Fiber-reinforced mycelium (FRM) composites offer an innovative and sustainable approach to construction materials for architectural structures. Mycelium, the root structure of fungi, can be combined with various natural fibers (NF) to create a strong and lightweight material with environmental benefits. Incorporating NF like hemp, jute, or bamboo into the mycelium matrix enhances mechanical properties. This combination results in a composite that boasts enhanced strength, flexibility, and durability. Natural FRM composites offer sustainability through the utilization of agricultural waste, reducing the carbon footprint compared to conventional construction materials. Additionally, the lightweight yet strong nature of the resulting material makes it versatile for various construction applications, while its inherent insulation properties contribute to improved energy efficiency in buildings. Developing and adopting natural FRM composites showcases a promising step towards sustainable and eco-friendly construction materials. Ongoing research and collaboration between scientists, engineers, and the construction industry will likely lead to further improvements and expanded applications. This article provides a comprehensive analysis of the current research and applications of natural FRM composites for innovative and sustainable construction materials. Additionally, the paper reviews the mechanical properties and potential impacts of these natural FRM composites in the context of sustainable architectural construction practices. Recently, the applicability of mycelium-based materials has extended beyond their original domains of biology and mycology to architecture.

Keywords: mycelium-based material; mycelium composites; fungi; construction biomaterial; natural fibers; fiber-reinforced mycelium

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1. Introduction

1.1. Sustainable Building Materials

The current economy for physical goods relies on extracting valuable resources, often ignoring their life cycle and environmental implications [1,2]. Research regarding sustainable building materials has increased in recent decades, driven by growing environmental concerns and the urgent need to reduce the construction industry's substantial carbon footprint [3–6]. Traditional construction materials, while robust, often involve energy-intensive manufacturing processes and contribute significantly to global CO_2 emissions.

The quest to substitute synthetic hydrocarbon-based plastics with natural polymeric materials is one of the most critical challenges in the international economy. Cellulose, the most generative biopolymer found in nature, remains the primary raw material for developing biocompatible and biodegradable materials. In conjunction with this, the mycelium of fungi, with its complicated network of tubular filaments known as hyphae, shares a similar structural morphology to cellulose fibrils. This similarity enhances the potential for mycelium to serve as a sustainable alternative in creating new biodegradable composites. These materials have the benefits of bio-composites, particularly their low embodied energy and biodegradability, emphasizing their environmental advantages and sustainability in building applications [1,7–9].

Extensive research is being conducted to improve fiber-reinforced composites due to their small size and low mechanical properties. However, they are suitable for applications where biodegradability and environmental impact are the primary concerns. Moreover, to improve the electrostatic properties, other studies use high-performance bamboo-based composite boards with enhanced hydrophobicity, compressive properties, dimensional stability, and mildew resistance, employing bamboo bundles and phenolic resin with nanoparticles. These composites demonstrate efficient electromagnetic dissipation and can be used in outdoor environments [10]. Another study produces a flexible fiber-based absorber with a high electromagnetic response by integrating heterostructures, nanostructure design, and π-conjugated polymer components. This results in an adequate absorption frequency bandwidth and enhanced electromagnetic attenuation, providing a reference for optimizing fiber-based flexible absorbing materials [11].

1.2. Mycelium as a Construction Material

Initially rooted in fields such as biology, mycelium was first used as a packaging material and, more recently, in construction as an insulator. In the last decade, it has evolved into an architectural decorative material. Today, its properties are being further explored by combining it with natural fibers to enhance mechanical strength for creating self-supporting structures [12]. Mycelium-based materials show a new approach to fabrication that focuses on growing materials instead of extracting them [13,14]. Mycelium's ability to bind organic substrates and its inherent properties as a self-assembling biological material make it appealing for eco-friendly construction applications. This work explores the potential of FRM composites as innovative and sustainable construction materials that could revolutionize the building industry.

Prototypological research proposed in the realm of architecture involves creating full-scale prototypes as tools for systematic investigation within a broader research context [15]. They emphasize a holistic and interdisciplinary methodology for developing new materials and construction technologies, mainly aimed at sustainable building practices. Also, ref. [1] investigates the use of mycelium as a building material, presenting a classification method that encompasses mycelium type, substrate combination, supporting structure, and post-treatment. The study features extensive architectural proposals developed with digital design tools, representing diverse approaches and strategies for integrating mycelium composite materials into architecture.

1.3. FRM as a Composite Material

Integrating non-biological or biological materials, such as synthetic fibers or NFs, into the mycelium matrix can improve its structural characteristics. Specifically, the fibers increase tensile strength and the material's resistance to fracture under load by acting as reinforcement.

Mycelium composites are gaining attention as a viable, sustainable material in the construction industry, combining the environmental benefits of NF with the regenerative properties of fungal mycelium. These composites are renewable and biodegradable and offer significant energy savings during production as they grow at ambient temperatures and utilize organic waste as substrates. With excellent thermal and acoustic insulation properties, these materials are ideal for applications such as insulation panels and interior design elements [16]. Although challenges remain in outdoor durability and large-scale production, continuous research and development enhance their structural integrity and scalability. As the construction industry moves towards greener alternatives, natural FRM composites represent a promising step forward, aligning with global sustainability goals and potentially transforming construction practices to adopt ecological responsibility [17].

It is well-known that humanity recognizes the significant potential of natural fibers (NFs) as alternatives to petroleum-based materials. In addition, NFs are appealing due to their lower cost, high availability, and diverse feedstock options [18]. By incorporating NFs to enhance the mechanical properties of mycelium, this research explores the behavior of mycelium composites which are not only environmentally sustainable but also mechanically competitive with conventional materials. This study delves into the properties of these composites, assessing their strength and durability and focusing on their application in non-load-bearing structures and in potential load-bearing structures. Through laboratory experiments and real-world testing, the work aims to demonstrate that FRM composites can offer a viable, sustainable alternative to traditional construction materials, aligning with global sustainability goals and advancing green building technologies.

NFs are increasingly popular for several reasons, including their potential to replace synthetic fiber-reinforced plastics at a lower cost while enhancing sustainability. Many studies [19–21] have widely acknowledged the contribution of NFs to improving composites. Meanwhile, another study [22] summarizes NFs benefits and drawbacks.

Mycelium composites, with their foam-like properties, are well suited for non-structural construction applications, such as thermal insulation and door cores. Their inherent structure, even without a specified pore size, makes them effective construction materials [23].

During the last decades, several kinds of fibers have faced the abovementioned demands in the construction industry. Experimental studies and modeling have shown that including fibers improves bond characteristics in structural concrete. Adding short fibers in concrete mass offers a composite material with advanced properties, and fiber-reinforced concrete is a promising alternative in civil engineering applications. Synthetic fibers are included in concrete developments in a new composite material that exhibits different cracking performance and overall behavior to plain concrete. A notable impact of synthetic fibers on enhancing post-peak compressive behavior was observed, highlighting the potential of fiber-reinforced concrete to offer enhanced ductility [24,25]. Also, according to the main finding of the paper by Imanzadeh et al., increasing the silt-to-binder ratio improves the material's ductility, while the inclusion of flax fibers significantly aids in maintaining cohesion and ductility after the peak stress point [26].

Meanwhile, the utilization of nondestructive techniques that account for the scattering of fracture energy within the microstructure has proven to be of great importance in understanding crack propagation and damage distribution across the fracture surface [27]. These methods have shown a strong correlation between the elastic and mechanical properties of fiber composites and can effectively characterize the bonding interactions between fibers and the matrix [28,29].

Mycelium is a composite fiber from natural polymers such as proteins, chitin, and cellulose. Those fibers create the mycelium's structural network, adding flexibility and lightweight properties [30]. Incorporating wood sawdust into mycelium composites significantly improves material properties, enhancing mechanical strength and thermal insulation. The mycelium body consists of a complex network of hyphae, elongated cells enclosed within a tubular cell wall and separated by internal septa. This structure strengthens the mycelium and supports its growth and ecological functions. The interconnected, fibrous web enhances compressive and tensile strength. Chitin, a natural biopolymer, is essential for creating strong fibers due to its long molecular chains that form tight, stable bonds. This characteristic provides structural integrity and stability to materials like mycelium-based composites, greatly improving their mechanical strength and durability [31]. Chitin nanofibers from fungal mycelium create a robust network that enhances mechanical properties. Generally, mycelium fibers from fungi like Pleurotus ostreatus offer higher compressive strength than traditional insulators, enhanced structural integrity, and durability. Meanwhile, they have already been applied to construction, furniture, architectural elements, and insulation applications, with a focus on sustainability and functional properties [32,33]. Many researchers have focused on the mechanical properties of mycelium structural networks, considering different variables and conditions of loading types of materials and environmental stress. The examination of the mechanical properties of mycelium composites under different stress conditions showed that bamboo microfibers can significantly enhance the material's structural integrity and suitability for various applications where mechanical strength is essential [34]. Moreover, optimizing the substrate composition for mycelium-based bio-composites (MBCs) maximizes mechanical strength and minimizes the ecological footprint for construction applications [35]. In this research, mechanical testing has been applied to different material blends to find the optimal balance between mechanical properties and environmental sustainability. Fungi-based binders in composite materials offer an environmentally friendly alternative to synthetic adhesives, reducing harmful emissions and improving mechanical strength [36].

Natural Fiber Reinforcement for Architectural Heritage and Self-Healing Structures

Nowadays, fiber-reinforced strengthening systems are commonly adopted to repair and reinforce historic masonry structures as an alternative to conventional systems. New composite materials are designed to preserve and enhance historical and architectural heritage vulnerable to environmental and seismic actions. They consist of a natural hydraulic lime-based mortar reinforced with randomly oriented sisal short fibers. This innovation in fibrous mortars significantly improves durability and resilience, offering a novel solution for heritage conservation and durability of restoration intervention. Natural-fibrous lime-based mortars are recommended to retrofit historic buildings, enhance earthquake performance, and reduce the construction's carbon footprint [37]. Composite materials are currently one of the most effective solutions for reinforcing and repairing existing structures, including architectural heritage. However, the construction sector must address environmental concerns, compatibility with existing substrates, and material durability. Growing ecological awareness and international regulations have driven research into bio-composites, leading to increased attention on natural fiber-reinforced composites. Natural fiber-based composite materials exhibit a wide range of mechanical properties due to the strong influence of fiber type on their characteristics [38].

Research on developing renewable, biodegradable, and eco-friendly materials has been gaining interest, as alternatives to synthetic materials are crucial to reducing anthropogenic impact on suffering ecosystems. Lignocellulosic fibers are a promising source for bio-based substitutes as they allow for the better use of agricultural waste. Traditionally, lignocellulose-based materials are made using formaldehyde-based resin binders, which are derived from fossil fuels, are toxic, and require a lot of energy to produce. However, the focus has shifted towards replacing these with more sustainable biological binders such as mycelium. Also, the addition of bacterial cellulose to mycelium composite materials strengthens the internal bonding of mycelium material and renders the material's tunable mechanical properties [39]. Extensive research has therefore been performed on using microorganisms for biologically mediated self-healing of concrete using $CaCO_3$ precipitation. As crack formation is an inherent concrete flaw, inspection, maintenance and renovation costs are inevitably high. The review study [40], provides conceptual directions and insights into the potential of mycelium fiber for the self-healing of concrete damages with a focus on fungal biomineralization functions while providing a synopsis of potential fungal prospects suitable for the application. In difference to bacteria, filamentous fungi grow in extensive mycelium webs with branched filamentous-shaped hyphal structures that allow them to fill and deposit $CaCO_3$ in more extensive damages.

1.4. Mechanical Properties of the FRM

One of the primary challenges in utilizing mycelium for large-scale structural applications is its inherent weakness, typically exhibiting compressive stress of only 0.1–0.2 MPa without mechanical compaction, and it performs optimally under compression. However, mycelium-based materials are exceptionally lightweight, offering favorable strength-to-weight ratios relative to concrete, which indicates that strategic material placement could enable the construction of large-scale and extended-span structures. Another study [41] discusses various strategies to strengthen and enhance myco-materials, specifically through the use of mechanical compaction and advantageous and target material placement. Mechanical compaction increases the density and structural integrity of the mycelium composites, enhancing their load-bearing capacity. Additionally, strategic placement of the material in structures optimizes the inherent strength-to-weight ratio of mycelium, making it suitable for larger and more ambitious architectural applications despite its natural limitations in compressive strength. These methods collectively aim to exploit the lightweight nature of mycelium while addressing its structural weaknesses for broader construction uses. The concept of strategic material placement for strengthening and enhancing myco-materials primarily involves designing the mycelium composite's layout and orientation to align with a building project's structural demands. Mycelium can be encouraged to grow in specific directions to align the fibrous network along lines of stress, which can improve the tensile and compressive strength of the material. This is relative to grain direction in wood, where the material is stronger along the grain than across it.

Myco-materials can be compressed or pre-stressed during curing to increase their load-bearing capacity, analogous to pre-stressed concrete. Applying internal pressures to the material enables it to withstand higher external stresses while in use. The strength of myco-materials can also be more effectively exploited through different architectural forms such as arches, domes, or vaults that naturally distribute loads efficiently. These structures are useful for dispersing stresses and lessening the dependency on the intrinsic strength of the material [42]. The study of [43] showed that using cold- or hot-pressing procedures to create dense panels from mycelium materials can substantially enhance the composite's mechanical characteristics by making it more compact and less porous. Furthermore, it reduces thickness while making it less complicated for fibers to rearrange themselves horizontally in a plane, resulting in more significant interaction between fibers at overlapping points. The pressing temperature significantly impacts the mechanical characteristics of the mycelial-based materials [31]. In addition, according to another research by [13], different types of fiber impact the mechanical properties and ability of mycelium composites to be produced. In comparison to cold-pressed and non-pressed samples, heat-pressed samples have greater tensile strength and stiffness and appear to be more brittle. Also, changes in the substrate and type of fungus can affect the thickness of the fungal skin and the homogeneity of the material, which can lead to modifications in the mechanical properties.

The objective of the authors in this study is to provide a detailed review of the properties of FRM composites, including density, compressive strength, and flexural strength. This review synthesizes insights to identify major challenges associated with expanding the use of mycelium-based materials as load-bearing structural components, particularly when integrating natural fibers into the matrix. This analysis will also illuminate potential opportunities and direct future research efforts.

After conducting a standardized and comprehensive review of publications on FRM in engineering and material sciences, the number of publications on this topic was detected to be quite limited. This critical review proposes a novel classification system for these materials to help structure and standardize this emerging transdisciplinary field of knowledge in building construction.

2. Adhesive Features in FRMs Composites

The methodology investigates the mechanical properties of mycelium-based biocomposites reinforced with NFs, focusing on key properties such as density, compression, and flexural strength. It also investigates how these properties interact with each other in mycelium construction. The review emphasizes the composites' potential as construction material, with an emphasis on the contribution of NFs to the composite. The section mainly focuses on the natural materials used by the researchers to develop FRM composites [23].

Research was conducted using four databases: Web of Science, Scopus, Science Direct, and Google Scholar. The search focused on articles using combinations of the keywords

"Natural Fiber-reinforced Mycelium Composite for Construction Building Materials". Articles that fell outside the realms of engineering, construction, building technology, or architecture were excluded. The selection process involved reviewing the titles, abstracts, and materials and methods sections of the articles to gather data on mechanical properties such as compressive strength, density, and flexural strength. Subsequently, these data are processed and compared to draw insightful conclusions regarding combining NFs with mycelium to develop robust construction materials.

2.1. Improving Adhesive Characteristics of Mycelium

The process for creating all the different mycelium composites follows the same method of procedure [44]. When a fungus degrades a substrate to obtain nutrients, it generates mycelium, which is a highly interconnected network of filaments called hyphae. These long cells bind the substrate's particles together, creating a mycelium-bound composite. Specifically, when a fungus grows on a particulate-based lignocellulosic substrate, the fungal cells form filaments called hyphae, creating a porous interconnected structure that binds the substrate's particles together. Meanwhile, developing mycelium-based adhesives is one area with considerable interest. These types of adhesives have demonstrated promise in various applications, including packaging, textiles, and the construction industry. Nowadays, many researchers [45–47] are attempting to enhance mycelium's adhesive abilities and determine the primary challenges and possibilities in this field. Specifically, they utilized the variables influencing the adhesive qualities of mycelium, including the selection of fungal species, substrate composition, and processing procedures.

2.1.1. Type of Mycelium

Different species may influence the material's density, tensile strength, and compressive strength. Hence, the exact kinds of mycelium utilized can vary depending on the bio composite's planned characteristics. Various fungal species exhibit differences in hyphal characteristics, including diameter, cell wall compositions, and branching patterns, which directly impact the density and tensile strength of the mycelium network and its substrate-binding capacity. Some fungi, like Pleurotus ostreatus, form a dense mycelium layer, known as fungal mycelium skin, between the substrate and the air, enhancing composite strength. Enzymes secreted by fungi degrade lignocellulosic materials in the substrate, with enzyme type and efficiency varying between species, influencing substrate degradation rates. Additionally, fungal species have distinct growth rates and environmental requirements, further affecting mycelium development and strength. Ultimately, the strength and applicability of mycelium-based composites hinge on the symbiotic relationship between selected fungal species and substrates [42,48,49].

2.1.2. Growing Conditions

The mycelium growing conditions have a major impact on the adhesive strength and durability of materials based on mycelium [50]. The variation in adhesive effectiveness among various fungal strains and environmental circumstances presents a major obstacle to attaining consistent and dependable adhesive characteristics [45]. There are several strategies that can be explored to enhance the adhesive properties of mycelium-based materials. The first strategy involves optimizing growth conditions. Meticulously controlling temperature, humidity, and nutrient availability during mycelium's growth can improve its adhesive properties. Machine learning models analyze results from numerous tests to predict specific mechanical properties and recommend processing parameters that enhance strength and performance. This approach is more efficient and less resource-intensive than conducting extensive experimental testing to determine the optimum conditions [47]. A predictive model establishes the relationship between compressive strength and split tensile strength for engineered cementitious composites [51]. Based on the aforementioned results, the type and ratio of fibers have a significant impact on the strength of engineered cementitious composites. Research has already indicated that specific combinations of these growth conditions can lead to mycelium with enhanced adhesive characteristics.

To maximize the potential of mycelium-based composites, future research should focus on optimizing growth conditions. Incorporating a vacuum system or an intake airflow system in the incubation chamber can enhance oxygen diffusion during inoculation. However, it is important to maintain optimal relative humidity to prevent the substrate from drying out, which could impede mycelium growth. Additionally, expanding the range of applications for mycelium-based composites and leveraging current study insights will be crucial for advancing this emerging field [52,53].

2.1.3. Substrate Selection

The substrate is any material or substance upon mycelium development. It functions as a supportive structure. The composition of the substrate on which the mycelium grows can also significantly determine its adhesive properties. Using substrates rich in cellulose, hemicellulose, and lignin has promoted better adhesion of mycelium-based materials. In the mycelium-based composites, the substrate is the material base that provides nutrients and a structure for the mycelium to colonize and grow, such as sawdust or agricultural waste. For this purpose, optimizing mycelium growth and defining the more suitable characteristics of the composite material requires evaluating the substrate's composition and characteristics. The finalized composite material's density, strength, and growth rate are all significantly impacted by the type of substrate employed, including agricultural waste, sawdust, and straw [54].

Mycelium-based materials benefit from the strain-hardening properties of intact NF substrates, which provide strength and inhibit shear failure [46]. Sawdust, straw, jute, hemp fibers, and textile waste are examples of fibrous substrates essential to creating mycelium-based composites. These substrates have special qualities that can greatly influence the final composite material's attributes. Their fibrous structure acts as a scaffold for mycelium's growth and intertwining, enhancing the finished composite's mechanical strength and durability. The final mycelium-based composite's compressive strength and load-bearing capacity will depend on the kind of substrates used [48].

Any thin, elongated material that is much longer than it is wide is commonly referred to as a fiber. Fibers may be synthetic, like polyester or nylon, or natural, like cotton, wool, or silk. Fibers are utilized in materials because of their strength, flexibility, and ability to be woven into greater textiles or added to composite materials for enhanced structural integrity. Furthermore, the phrase "fiber" can also refer to additives, including cotton or soy silk fibers, merged into the substrate to alter the final composite's physical qualities, increasing characteristics like durability, flexibility, and tensile strength. Researchers found that the mechanical strength is more significantly influenced by the size of the fibers [13]. Mycelium can grow on a substrate, even on a fiber substrate. However, incorporating NFs into the substrate can enhance the mechanical properties and structural integrity of the resulting mycelium-based composites, making them more suitable for load-bearing applications [4].

2.1.4. Genetic Engineering

Genetic engineering of fungal strains to enhance strong adhesive properties can result in better-performing materials [47]. Using certain chemicals or biological agents during the growth process can enhance the mycelium's inherent adhesive qualities [46]. Advanced processing techniques like compaction, extrusion, and 3D printing can affect the density and structural integrity of mycelium-based materials, thereby influencing their adhesive strength [31]. Molecular-level modifications using nanotechnology to alter the mycelium's surface characteristics could improve interface bonding with different materials. Combining mycelium with other natural or synthetic adhesives, fibers, or materials in hybrid composites can exploit synergistic effects to enhance overall adhesive strength. The collaborative interaction between mycelium and other fibers can result in improved mechanical characteristics, such as heightened strength, durability, and resilience to compression [55].

2.1.5. Additives

The promising approach is the use of additives to enhance the adhesive characteristics of mycelium-based materials. Integration of specific additives during the mycelium growth process has the potential to modify the final adhesive properties, making them more suitable for diverse applications. Nowadays, many researchers are exploring ways to improve mycelium's adherent properties and identify the primary obstacles and potential opportunities in this field [45,46,56,57]. In addition, by strengthening the internal connections between the hyphae and the NFs inside the composite, adding bacterial cellulose to mycelium composites improves their adhesive properties. Due to its nano-fibrillar form, bacterial cellulose can interlock with the hyphae of mycelium to enhance the contact surface.

Existing research provides substantial evidence for the potential to enhance the adhesive properties of mycelium-based materials by developing advanced processing techniques, investigating additives and pretreatments, and regulating growth conditions. This results in a more cohesive composite material with greater strength and durability, addressing one of the key challenges in developing mycelium-based materials, which is the otherwise weak internal bonding. The incorporation of bacterial cellulose thus results in a strengthening of the mycelium material's overall structure [39]. Sharma and Sumbia used miscanthus, a C4 grass, as an additive to enhance the properties of mycelium [23].

2.1.6. Manufacturing Processes and Treatments

The development of advanced processing techniques, such as compaction and extrusion methods, can also contribute to improving the adhesive properties of mycelium-based materials [23,56]. Compaction can improve the bond between mycelium and the reinforcement fibers or achieve more satisfactory material homogenization through extrusion, significantly enhancing the composite's structural and environmental performance. These techniques offer the possibility of creating denser and more structurally sound materials, which could lead to enhanced adhesive strength and durability. Investigating the consequences of various processing techniques on the adhesive properties of mycelium-based materials would be a valuable prospect for further research.

Once the mycelium has grown through the substrate and around the fibers, halt the growth by drying or heat-treating. This step is crucial to maintaining the material's structural integrity and preventing further biological activity that could compromise its properties. Depending on the application, the composite may need to be post-processed by machining, pressing to the desired density, or applying surface treatments to enhance durability or appearance.

Utilizing mycelium-based bio-composites involves optimizing their substrate composition and production methodology. Primary processing methods typically include drying or heating to complete the formation of mycelium composites [35]. The main steps can be described by (i) drying, which typically involves removing moisture from the composite material at room temperature or in an oven at a controlled temperature. This process terminates the growth of the mycelium and solidifies the structure of the material and (ii) heat treatment, which similarly stops the growth of the mycelium but is usually performed at higher temperatures than simple drying. This can also affect the material's structural properties, potentially increasing its strength and stiffness. The decision between drying and heating should be based on the specific properties desired for the final MBCs. Drying at lower temperatures might be less energy-intensive and could preserve more natural material properties. Heat treatment might enhance certain properties, such as durability, strength, and resistance to water or pests, but it could also be more energy-consuming and might alter the material's appearance or introduce additional stresses.

Ultimately, the choice of drying or heat treatment would depend on the specified goals for mechanical performance and environmental impact, as well as the nature of the mycelium species and substrates used. Each processing method would need to be evaluated based on the design criteria and environmental considerations for the optimal outcome [35].

2.1.7. Analytical Tools

Recent studies suggest several potential methodologies for enhancing the adhesive characteristics of mycelium-based materials. Optimizing growth conditions by precisely regulating factors such as temperature, humidity, and nutrient concentrations can improve the adhesive properties of mycelium [46]. Selecting substrates with high cellulose, hemicellulose, and lignin content, which are known to promote better adhesion, can influence the binding efficiency and mechanical properties of the resulting composite [13,46].

To enhance comprehension of the best suitable conditions leading to ideal adhesive properties, simulation, and machine learning techniques can be employed [47]. These techniques take a holistic approach, starting with the first mycelium synthesis and ending with the application in composite production. Combining these techniques can produce mycelium-based polymers with desired adhesive properties in various industrial applications.

2.2. The FRM Composite

To further improve the material's mechanical properties, the FRM composite, an innovative and sustainable material, combines the fungus's root structure and mycelium's inherent growing ability with various reinforcing NFs. In this way, the mixture produces a sustainable and biodegradable composite material, making it an appropriate replacement for traditional synthetic materials in various applications. Modifying the types of fibers induced and the mycelium's growth conditions allows for customizing the composite's mechanical properties, including strength, flexibility, and durability. In general, FRM composites offer many enchanting possibilities for their mechanical properties. Nonetheless, FRM composites require methodical attention to their long-term durability under diverse environmental conditions, property uniformity, and scalability. To conquer these challenges, researchers are working diligently to expand the material's range of applications and solidify its position as an essential part of sustainable manufacturing. Moreover, the distinct characteristics of NFs can be customized to fulfill the demands of various uses. Hemp fibers, for instance, are renowned for having a high tensile strength and are stiff, which makes them appropriate for uses in which structural integrity is crucial. However, flax fibers are highly flexible and resistant to impacts, which makes them perfect for applications where toughness and resilience are critical [58]. NFs and mycelium improve the composite's mechanical qualities and make it more sustainable by using biodegradable and renewable resources. When combined with NFs, materials built on mycelium can become more robust. While mycelium alone exhibits exceptional adhesive properties and is able to create a cohesive matrix, implementing NFs to the composite enhances its mechanical characteristics, particularly flexural and compressive strength. NFs have a high strength-to-weight ratio and natural toughness. They serve as reinforcement within the composite structure whenever combined with mycelium, propagating stress uniformly while improving overall durability. The material is more resistant to bending, stretching, and impact pressures due to the fibers' additional reinforcement and ability to prevent cracks from spreading all through it. A composite material that is stronger and more resilient than pure mycelium-based materials results from the synergistic interaction between mycelium and NFs.

2.2.1. Fiber Type Selection

NFs are composites with high-strength cellulose implanted within a lignin matrix. Therefore, high cellulose content corresponds to an increased tensile strength. Some fibers, in addition, contain a waxy external layer that supplies natural safety that offers against bacteria and other potential sources of infection. NFs can be categorized according to their root and grouped into leaf: abaca, cantala, curaua, date palm, henequen, pineapple, sisal, banana; seed: cotton; bast: flax, hemp, jute, ramie; fruit: coir, kapok, oil palm; grass: alfa, bagasse, bamboo and stalk: straw (cereal). The work of Girijappa et al. provided an overview of various sources of NFs, their inherent properties, methods for modifying NFs, and the impact of treatments on their characteristics [59]. It also summarizes the primary applications of NFs and their efficient utilization as reinforcements for polymer composite materials.

Overall, the key factor is the proper integration of the fibers with the mycelium matrix, which can create a material with markedly improved mechanical properties suitable for various applications, including certain architectural elements [60].

2.2.2. Fiber Preparation and Surface Modification

The performance of natural fiber-reinforced polymer composites depends on various factors, including the chemical composition of the fibers, cell dimensions, microfibrillar angle, defects, structure, physical and mechanical properties, as well as the interaction between the fibers and the matrix. The primary drawbacks of using NFs as reinforcements in composites include their insufficient compatibility with the matrix and their tendency to absorb moisture. Consequently, modifications to NFs are often undertaken to enhance their surface properties, thereby improving their adhesion to various matrices. With a robust and well-bonded interface, exceptional strength and stiffness can be achieved, although this may result in a brittle composite that allows cracks to propagate easily through the matrix and the fiber. Conversely, a weaker interface can diminish the efficiency of stress transfer from the matrix to the fiber.

The fibers are prepared by cleaning and sometimes treating them to enhance compatibility with the mycelium. This treatment could involve applying natural binders or adjusting the fiber surface for better adhesion. Treatment of fibers with alkali is also referred to as mercerization and it is one of the most used fiber treatment methods [61]. Alkaline treatment has the following impact on fibers: it releases certain amounts of wax, lignin, oil, and other impurities; it decomposes cellulose, which leads to the exposure of short-length crystallites; it improves the roughness of the fiber surface, thereby yielding better mechanical properties; and it improves the wettability of fiber surfaces [58].

A method for enhancing the adhesion characteristics of NFs is carried out by treating NFs with a fungus [62]. Treated fibers showed enhanced acid–base characteristics and resistance to moisture. Improved acid–base relations between fiber and resin are anticipated to enhance the interfacial bonding, whereas improved water resistance would benefit the durability of the composites. Finally, composites were designed using untreated/treated fibers and unsaturated polyester resin. Composites with treated fibers showed better mechanical properties, most probably due to improved interfacial bonding.

Physical methods incorporate stretching, calendaring, thermo-treatment, and the production of hybrid yarns to modify NFs. Physical treatments change the structural and surface properties of the fiber and thereby influence the mechanical bonding of polymers. Physical treatments do not extensively modify the chemical composition of the fibers. Therefore, the interface is generally improved via an increased mechanical bonding between the fiber and the matrix.

Chemical changes in NFs aimed at improving the adhesion within the polymer matrix were examined using various chemicals. Different methods, such as alkaline, silane, or other chemical treatments, have been developed to enhance fiber–matrix compatibility and improve composite quality. Although NF composites are still in development and their applications are limited, they hold great promise as a sustainable alternative to conventional materials [5].

The physical treatments change the surface and structure properties of the fibers without the application of chemicals and improve the bonding between the polymer matrix and the reinforcement fiber matrix thus increasing the strength of the fabricated composites [63]. Physical techniques like corona treatment are used for surface oxidation activation. This process modifies the surface energy of cellulose fibers. Corona discharge treatment on cellulose fiber and a hydrophobic matrix was found to effectively enhance the compatibility between hydrophilic fibers and a hydrophobic matrix [58].

Each treatment type can induce specific changes in the surface layers of NFs. However, the overarching objective is to enhance the physical and chemical interactions between the fiber and the matrix, aiming for exceptional composite material performance [20].

The decision impacts not only the handling and durability of the material but also its structural integrity and load-bearing characteristics. Drying, which induces dormancy, allows for potential continued growth under suitable conditions, possibly affecting long-term stability and strength. On the other hand, heating permanently halts growth, possibly leading to more consistent characteristics over time. After cultivation, drying or heating is used to stop mycelial growth. If this is conducted through slow drying, the evaporation of water from the mycelium and the substrate could create a lightweight, porous material with closed-cell structures, much like foam. However, this porosity could compromise compressive strength. Conversely, rapid or uneven drying might create internal stresses that reduce structural integrity. Heating often removes moisture more thoroughly and kills the mycelium, leading to a fixed internal matrix, which might result in increased compressive strength but also potentially greater density due to shrinkage and solidification of the composite components [64].

If the substrate is dense or the growth conditions do not promote strong binding and development of a robust mycelial network, the resulting material may be dense without being particularly strong in compression [65].

2.2.3. Combining Mycelium and NFs

The fibers blend with the mycelium substrate, typically consisting of mycelium spores and a nutrient base like agricultural waste products. Ensuring a uniform distribution of fibers throughout the matrix is essential to achieve consistent strength. The mixed material is placed into a mold to shape the composite. The mycelium then needs to be adequately inoculated to start the growth process. Integrating fibers with the mycelium matrix correctly is crucial for creating a solid and durable composite. The composite processing ingredients, as depicted in Figure 1, consist of mycelium, fibrous substrate, and additional NFs.

Understanding the mechanisms of the mycelium networking process provides insights into how these composites achieve their unique properties. For optimal coverage, an active surface on both the NF and the mycelium fiber is essential to maximize the bonding effect at the interface between them. As can be depicted in Figure 1, the bonding effect between mycelium hypha fibers and NFs. The biological mechanisms of the mycelium networking process enable mycelium–fungal networks to expand in response to their environment, forming complicated, interconnected structures.

The interface, where two distinct materials converge, is crucial for transferring stress and preventing delamination. Figure 1 also shows the bonding effect in the interface zone. Cultivating mycelium hypha fibers enables them to grow and establish connections with the treated NFs. Simultaneously, the mechanical and chemical interface between layers of NFs is developed and strengthened as the mycelium hypha fibers integrate, resulting in a robust composite structure.

The mechanisms of mycelium networking in composite materials involve the interfacial bonding between mycelium hyphae fibers and natural fibers (NFs), essential for maximizing mechanical performance. This bonding strengthens the structure by reinforcing the matrix, distributing stress more evenly, and effectively bridging micro-cracks to prevent their propagation within the composite material.

The key differences from other traditional fiber composites are as follows:

- Mycelium materials are fully biological and sustainable while other traditional composites often use synthetic polymers.
- Mycelium materials are biodegradable and can be grown using less energy and have lower environmental impact compared to the production of synthetic polymers.

- In mycelium materials, which contain hyphae—a dynamic growing variable—the precise mix proportion is not initially precisely known, unlike in traditional composites where the mix proportion is defined at the outset.
- Traditional composites offer higher strength and durability than mycelium-based materials. However, mycelium composites are continuously being improved and may find appropriate applications where lower mechanical properties are acceptable.
- Traditional composites often require high-temperature processing and chemical additives, whereas mycelium materials grow at room temperature and use biological processes.

While the basic principle of creating a composite material is similar—reinforcing a matrix with fibers—the bonding mechanisms and the materials used differ significantly, reflecting their varied applications and environmental impacts.

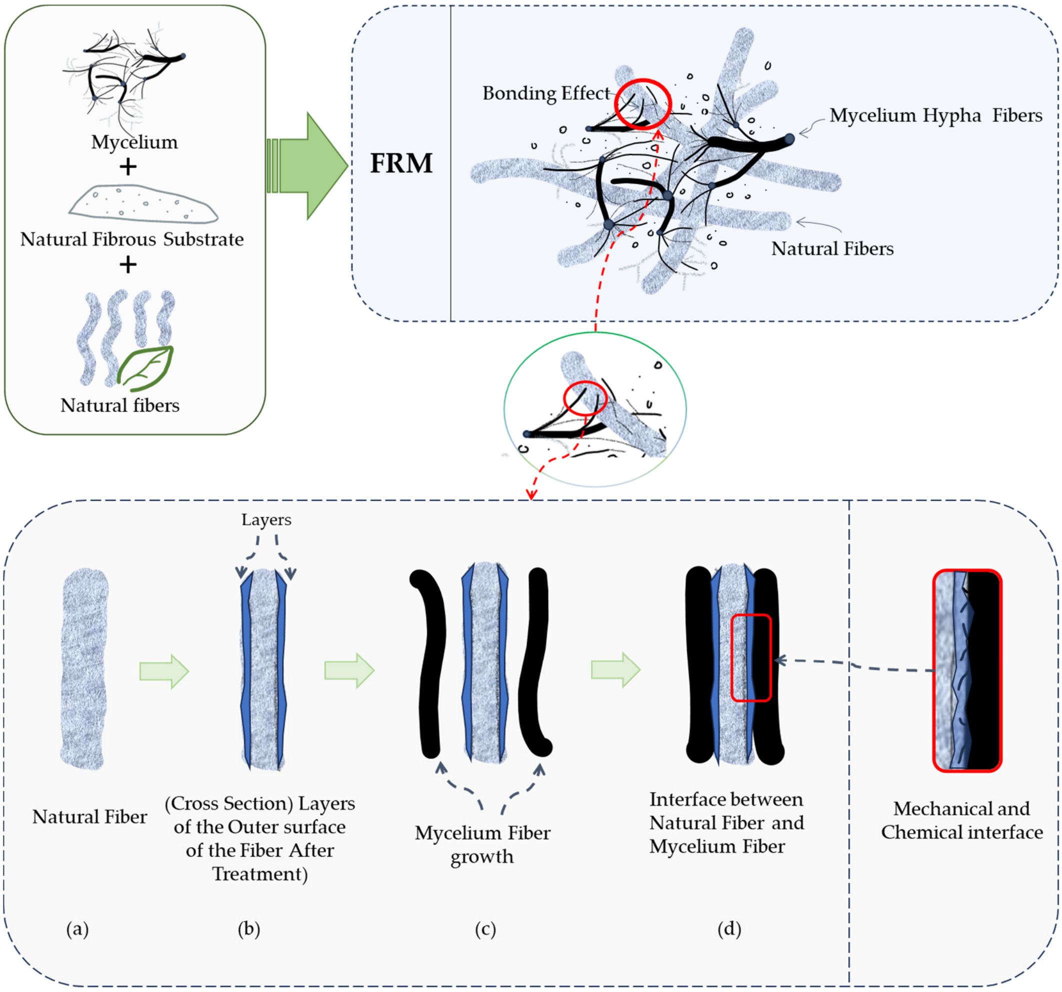

Figure 1. FRM composite and bonding effect in the interface zone. There are four steps: (**a**) NF; (**b**) treatment of the NF; (**c**) cultivation of mycelium hypha fibers, allowing them to grow and establish connections with the treated NFs; (**d**) the interface between layers of NFs is developed and strengthened as the mycelium hypha fibers integrate, forming a robust composite structure.

2.2.4. Fiber Distribution and Bonding

As the fiber content increases, the distribution of fibers within the composite may become less uniform. This can create weak points or areas with less effective stress transfer. Additionally, higher fiber content can interfere with the bonding between the fibers and the matrix (the surrounding material that holds fibers together), which is crucial for transferring loads effectively throughout the composite [35]. Natural fiber-rich substrates provide properties like hardening of the strains to mycelial products by giving them strength and avoiding failure due to shear [31,56]. The impact of the fibrous fiber content on the properties of the mycelium composites results from the interaction between the mycelium's natural network formation and the structural qualities provided by the fibrous materials. The precise effects depend on factors like the type of fibrous material, its proportions within the composite, and the mycelium's growth and processing conditions.

The mechanical characteristics and the durability of the resultant composite can be improved by altering the surface of the fibers using suitable treatments by enhancing the physical and chemical interactions between the fiber and the matrix [20,66]. Moreover, NFs have a hierarchical structure comprising primary and secondary layers that control the mechanical behavior of plant fibers and, in turn, the properties of composite materials into which they are included [21,67].

Mycelium materials use fungi's root structure to bind natural substrates, which can include plant NFs, agricultural byproducts, or other organic materials. Figure 2 depicts one type of building element.

Figure 2. Building element from ganoderma lucidum mycelium cultivated in a hemp fiber substrate. One of the three types of building elements with different geometry produced in the context of a diploma thesis in the Department of Architectural Engineering.

2.3. Problems in the Addition of NFs in MBCs

Although increasing the strength is preferable, the NFs might sometimes stiffen the composites. The mycelium fiber network's inherent structure lowers its deformation and bending capacity, which could diminish its flexibility and increase the material's brittleness and fragility. The equilibrium between the benefits and potential drawbacks, such as handling brittleness, water absorption, and the processing difficulties associated with incorporating fibers into the mycelium matrix, is a complex interplay of several variables. These include the fibers' type, quantity, orientation, production method, and mycelium's development properties, all of which significantly influence the final outcome [4,7,66].

3. A Comparative Review of The Mechanical Properties of FRM Composites

The respective mechanical tests evaluate the mechanical characteristics of FRM composites, such as density, compressive strength, and flexural strength, and it is crucial to assess their suitability as a construction material. Compressive strength is a vital characteristic that estimates a material's resistance to direct pressure from an applied compressive force. The value of the material's compressive strength is a criterion for usage in the building and construction industry. Meanwhile, the mycelium's growth substrate impacts its density. Some substrates might produce a denser mycelium network but do not necessarily enhance the binding quality, which is crucial for compressive strength. Flexural strength is a vital mechanical property indicating a material's deformation resistance under bending loads. FRMs, renowned for their outstanding flexural strength, owe this quality to the blend of a flexible matrix and high-strength fibers. This characteristic renders them well suited for various structural applications. Recognizing flexural strength is pivotal for discerning both the potential applications and limitations within construction and design when considering mycelium-based composites.

Table 1 shows the mechanical properties of the reviewed FRM composites from different studies. It also indicates the type of mycelium and the corresponding fibrous substrate for each referenced study.

Table 1. Mechanical properties of FRM composites for innovative and sustainable construction materials.

Type of Mycelium	Fiber Substrate	Density (kg/m^3)	Flexural Strength (KPa)	Compression Strength (kPa)	Reference	Studies
Coriolus Versicolor	Wood chips, hemp hurd, fiber	260		93	[65]	Lelivelt et al., 2015
Pleurotus ostreatus	Wood chips and hemp fiber	130	347	452	[68]	Etinosa 2017 Thesis
Trametes versicolor	Hemp	99		510	[13]	Elsacker et al., 2019
Trametes versicolor	Chopped hemp			770	[13]	Elsacker et al., 2019
Trametes versicolor	Chopped flax	135		1180	[13]	Elsacker et al., 2019
Lentinus velutinus	Sawdust and wheat bran			1280	[69]	Bruscato et al., 2019
Pycnoporus sanguineus	Sawdust and wheat bran			1300	[69]	Bruscato et al., 2019
Pleurotus Ostreatus	Sawdust 90% and wheat 10%	493		1380	[64]	Ghazvinian et al., 2019
Ganoderma sessile	Wheat straw	226		350	[57]	Attias et al., 2020
Trametes versicolor	Hemp	134		360	[70]	Zimele et al., 2020
not defined	Rice bran		916	4490	[71]	Ongpeng et al., 2020
not defined	Sawdust		962	7990	[71]	Ongpeng et al., 2020
Pleurotus ostreatus	Cotton stalk, wheat bran			508	[72]	Gou et al., 2021
Ganoderma lucidum	Wheat straws			70	[73]	Raut et al., 2022
Trametes versicolor	Hemp and 1.5% nanoclay	180	1470	123	[74]	Elsacker et al., 2022
Trametes versicolor	Hemp and 2.5% nanoclay	183	1470	123	[74]	Elsacker et al., 2022
Pleurotus ostreatus	Straw	132	370	210	[48]	Ghazvinian et al., 2022
Pleurotus ostreatus	Beech Sawdust	384	390	320	[54]	Sağlam et al., 2022

Table 1. *Cont.*

Type of Mycelium	Fiber Substrate	Density (kg/m^3)	Flexural Strength (KPa)	Compression Strength (kPa)	Reference	Studies
Lentinus squarrosulus	Rice husk			460	[75]	Ly et al., 2022
Lentinus squarrosulus	Coconut husk			470	[75]	Ly et al., 2022
Lentinus squarrosulus	Hemp			510	[75]	Ly et al., 2022
Lentinus squarrosulus	Rice straw			540	[75]	Ly et al., 2022
Ganoderma lucidum	Wood veneer and hemp hurds	145	160	1200	[76]	Özdemir et al., 2022
Ganoderma williamsianum	Sawdust		90	1850	[77]	Aiduang et al., 2022
Lentinus sajorcaju	Sawdust		110	1870	[77]	Aiduang et al., 2022
Pleurotus ostreatus	Beech Sawdust	260	110	2490	[78]	Vašatko et al., 2022
Trimitic fungi species	Baboo	180	450	190	[35]	Bagheriehnajjar et al., 2023
Pleurotus ostreatus	Small particle size ash wood chips			261	[32]	Grenon et al., 2023
Pleurotus ostreatus	Ash wood chips			399	[32]	Grenon et al., 2023
Pleurotus ostreatus fungi	Sawdust	336	300	456	[79]	Peng et al., 2023
Pleurotus ostreatus spawn	Bamboo			500	[34]	Soh et al., 2023
Pleurotus Ostreatus	Hemp hurds			700	[80]	Etinosa et al., 2023
Pleurotus Ostreatus	Coffee grounds with pineapple fiber	360	200	2920	[81]	Kohphaisansombat et al., 2023
not defined	Hemp	122	234	1246	[72]	Abdelhady et al., 2023

3.1. Density

There is a correlation between compressive strength and density in composite materials. Generally, as the density of a material increases, so does its potential for higher compressive strength because a denser material often indicates that there are fewer voids within the structure, which can increase its ability to withstand compressive forces. However, this relationship can be complex because, at some point, increased porosity or specific configurations of the internal structure might contribute positively to mechanical strength in certain composites. In the context of mycelium-based composites, the study [81] found that the composite reinforced with 10% natural pineapple fibers exhibited the highest density and, correspondingly, the highest compressive strength. This suggests that within this specific set of materials, there is a direct correlation where increased density, facilitated by the addition of reinforcing fibers, leads to increased compressive strength. Nonetheless, this trend can be influenced by other factors, such as the even distribution of fibers, matrix-to-fiber ratio, and the characteristics of the fiber and matrix materials.

In composite materials, density generally relates to compressive strength, although the relationship can vary depending on the specific material and its structure. Typically, a higher density in a composite material can imply a higher volume of solid material, which often contributes to greater compressive strength since there is more material to resist compression.

However, the correlation is not always linear as illustrated in Figure 3. If the increased density results from factors such as porosity or the incorporation of low-strength fillers, the impact on compressive strength may be inconsistent, and a clear increase in strength may not be observed. Conversely, if a material's higher density comes from the addition of high-strength reinforcements, the composite's overall compressive strength might increase significantly.

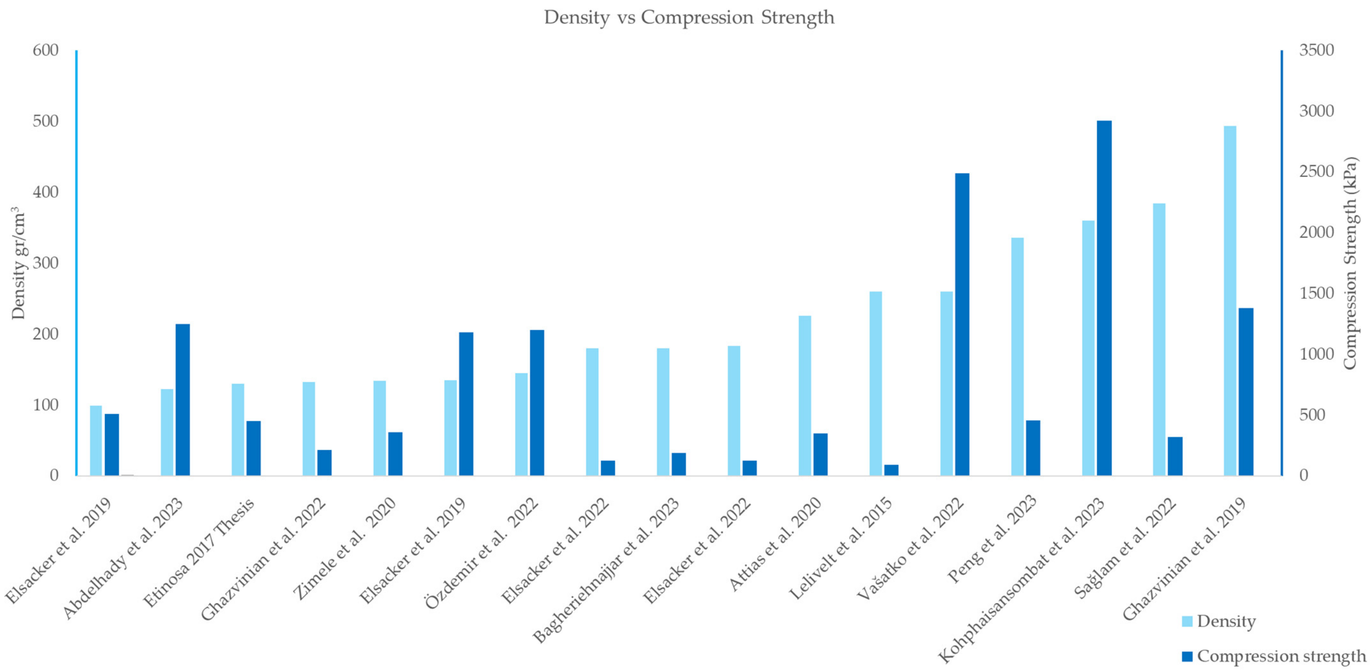

Figure 3. Correlation between compressive strength and density in FRM [13,35,48,54,57,64,65,68,70,72,74,76,78,79,81].

The specific architecture of the composite, including the type of matrix and reinforcement used, the bonding quality between them, and the internal structure (like the presence of voids or the distribution of the reinforcement within the matrix), can all dramatically influence how density and compressive strength are related. Some lightweight composites are engineered to have low density yet maintain high compressive strength through optimized microstructures and material arrangements.

In the cases involving mycelium-based composites, it is crucial to understand that their unique biological structure and the interaction with added substrates will influence both density and compressive strength in different ways compared to more conventional materials [78,80,82]. The variation in biological structural aspects refers to the species of mycelium, the growth conditions, such as temperature and humidity, and the metabolic activity of the mycelium during its growth phase. These factors substantially impact the structural integrity and mechanical properties of the resulting composite materials. The biological aspects of the relationship between density and compressive strength in fiber-reinforced mycelium composites are complex and inconsistent due to multiple influencing factors. Biological aspects primarily depend on the type of mycelium and its growth conditions. Environmental variations yield different mechanical properties for the same type of mycelium. Although higher density generally corresponds to greater compressive strength, this correlation can vary significantly based on factors such as the specific composition of fibers and matrix materials, the internal structural integrity including voids and reinforcement distribution, the type and strength of fillers incorporated, the presence and interaction of additives, and the nuances of the production processes employed. These variables collectively shape how density depends on biological aspects that affect compressive strength in mycelium composites, highlighting the complex interplay of material properties and manufacturing techniques in determining the mechanical performance of these innovative biomaterials.

3.2. Compressive Strength

The compressive strength of mycelium is a vital consideration in numerous applications, particularly in sustainable building materials. Understanding the factors influencing FRM composite compressive strength is essential for optimizing its potential for sustainable construction [35,45,48,57,74,78,80,82]. Figure 4 depicts the compression strength of various FRMs studied in the literature, arranged from the lowest value to the highest.

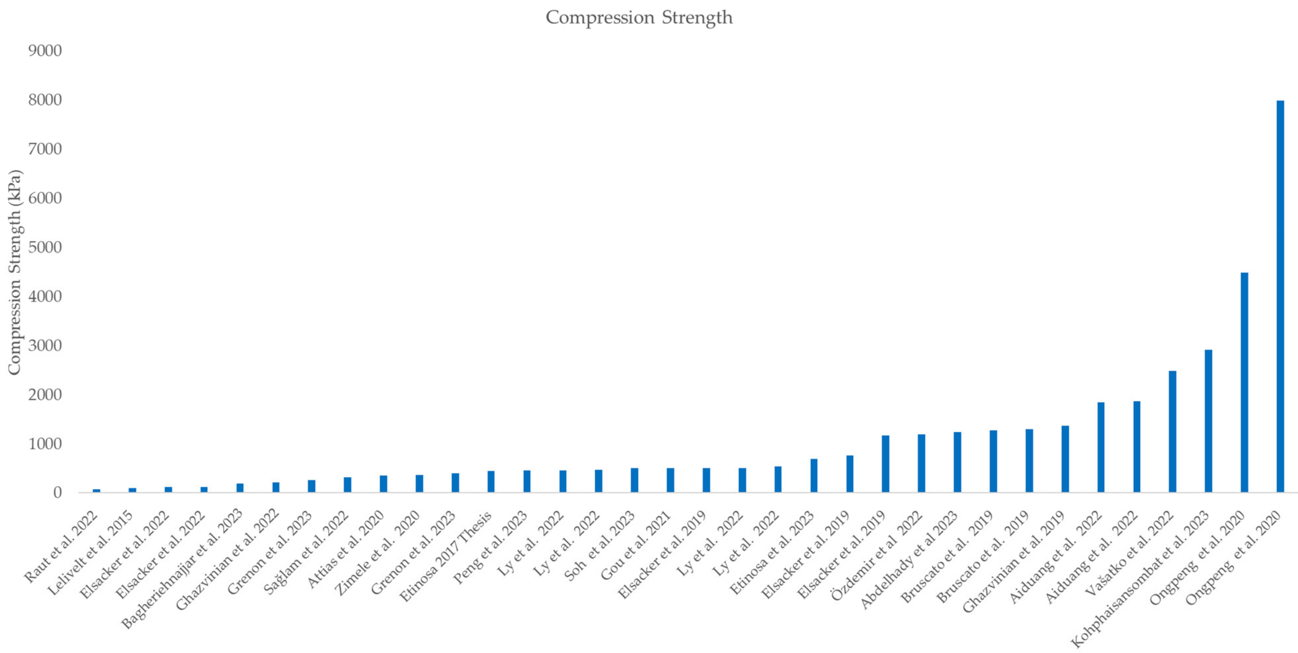

Figure 4. Compression strength per different studies in the literature [13,32,34,35,54,57,64,65,68–81].

Based on the research presented by Peng et al. [79] there is a relationship between compression strength and density in mycelium bio-composites. The density of the prepared mycelium bio-composites ranged from 0.249 g/cm^3 to 0.336 g/cm^3. The compression strength of the mycelium bio-composites ranged from 270.31 kPa to 456.70 kPa. The relationship between compression strength and density follows a general trend of higher density leading to higher compression strength.

The relationship between compressive strength and density in mycelium composites shows a slight tendency for compressive strength to increase with density. However, this trend is not consistent and is influenced by factors such as the presence of nanoclay and the specific composition of the composites. Therefore, there is no clear, consistent relationship between compressive strength and density. Other factors, including nanoclay and the composite composition, appear to have a more significant impact on the compressive strength of mycelium composites [74].

In mycelium composites, density is directly related to compressive strength. Higher density often correlates with greater compressive strength due to reduced porosity and increased mass per volume, which enhances the material's resistance to compression. As mycelium grows, it binds substrate particles, and densification of this network improves compressive strength. However, this relationship is influenced by factors such as the binding substrate, type of mycelium, and production process.

Effect of the NFs on the Compression Strength of FRM

The recent literature indicates that NFs play a crucial role in creating composite mycelium materials, especially for engineering structural applications. Adding bamboo fibers up to a certain percentage could enhance density and mechanical strength, while above a certain threshold, these properties might start to vary [35]. This work provides a comprehensive analysis and comparison of studies utilizing only NFs in constructing fiber-reinforced mycelium composite materials. Figures 5 and 6 depict the compression strength of various FRMs, classified according to the type of fibrous substrate and the type of mycelium, respectively. These visualizations offer insights into how different fibrous substrates and types of mycelium influence the compression strength of FRMs.

Among the various fibers, fine bamboo fibers are particularly effective in increasing the density and mechanical strength of mycelium composites [35]. Pre-compression further enhances these properties, making it a valuable process in producing high-density, high-strength mycelium-based materials. Conversely, when added to the substrate mix for mycelium-based composites, thick bamboo fibers led to a reduction in material strength due to their size and rigidity, resulting in less compactness and more pores within the final material. The sawdust thoroughly incorporates the finer bamboo strands, which are more pliable and may disperse more uniformly in the mold. Furthermore, due to their smaller size, finer fibers might be more readily ingested by fungi, which would facilitate the formation of a denser and more cohesive material structure.

The clear correlation between substrate density, MBC density, and compressive strength highlights the necessity of selecting the optimum substrate to maximize MBC performance in construction applications. Some studies have shown the importance of lignin in determining mycelium-based composites' mechanical properties [48]. In addition, the sawdust-to-straw ratio in the substrate mixture can significantly impact the density and compressive strength of mycelium-based materials. The physical and chemical differences between sawdust and straw affect the mycelium's growth behavior and the final composite's structural qualities. Because sawdust usually includes finer particles, it can pack the substrate more densely, increasing the density of the mycelium-based substance. Contrarily, straw is often more hollow and more fibrous, with less density when used alone.

The variety of fibers influencing the density originates from the different organic and agricultural waste materials in the mycelium composites. Specifically, in the context of mycelium-based composites, the type of substrate used, such as different types of agricultural waste (like straw or sawdust) and the inherent properties of those fibers, such as their size, porosity, and water absorption capacity, can significantly impact the final density of the composite material [42]. Additionally, the density of the fibrous additive, such as pineapple fibers or other NFs, can also impact the overall density of the composites [81].

Adding hemp fibers improves the mechanical properties of the mycelium-based foams, such as compression strength. The results were obtained from the compression test from the study of Picco et al., 2024 where it can be observed that the 50% PS-50% hemp fiber and 25% hemp fiber with 75% peanut shell combinations improved the compressive, reaching compressive strain values of 0.167 MPa and 0.117 MPa, respectively. The values for both were higher than those of the two expanded polystyrene materials tested for comparison. The 100% hemp fiber and 100% peanut shell materials were less rigid than the tested expanded polystyrene, signifying that mixing is beneficial for achieving better properties [83].

From the above studies, the inclusion of natural fibers significantly enhances the compression strength of mycelium composites, making them more suitable for construction applications. Fine bamboo fibers and sawdust improve density and strength, while thick bamboo fibers can reduce strength due to increased porosity. The optimal combination of substrates, such as sawdust and straw, is essential for better results. Hemp fibers specifically enhance compression strength. The research highlights the importance of substrate and fiber selection in developing high-performance, sustainable mycelium-based construction materials.

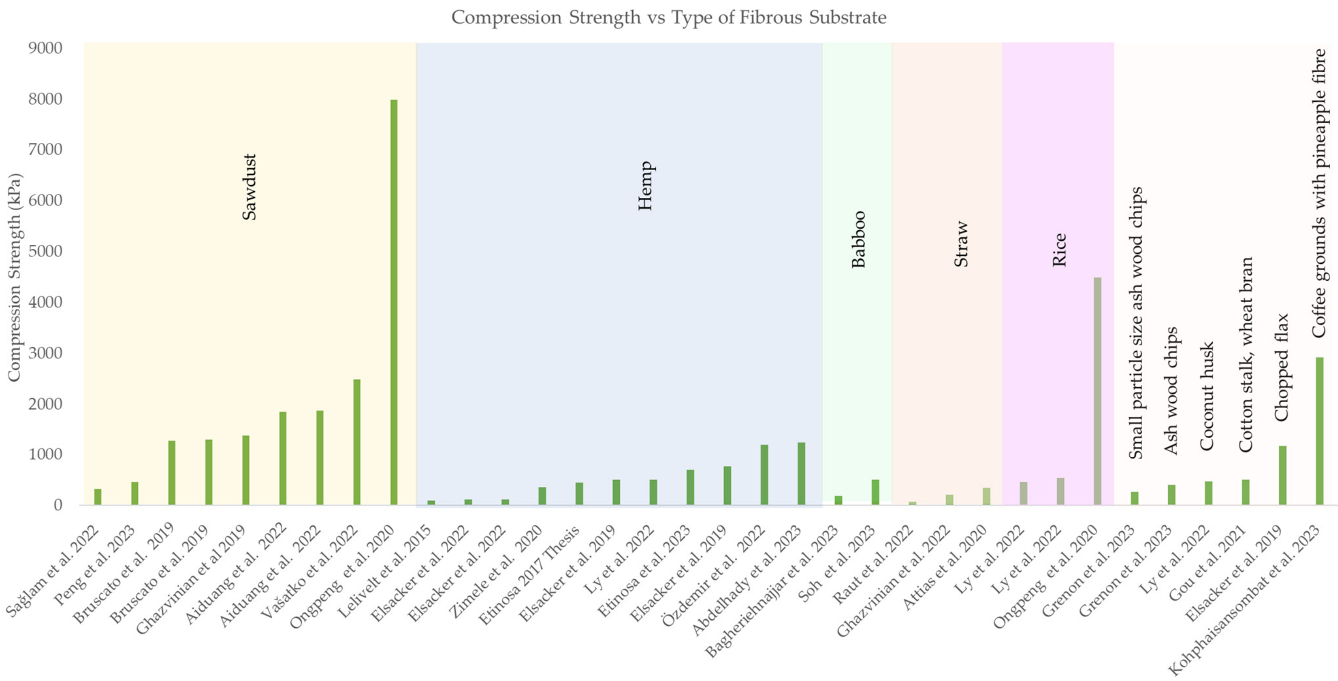

Figure 5. Compression strength per different studies in the literature. Classification of type of fibrous substrate [13,32,34,35,54,57,64,65,68–81].

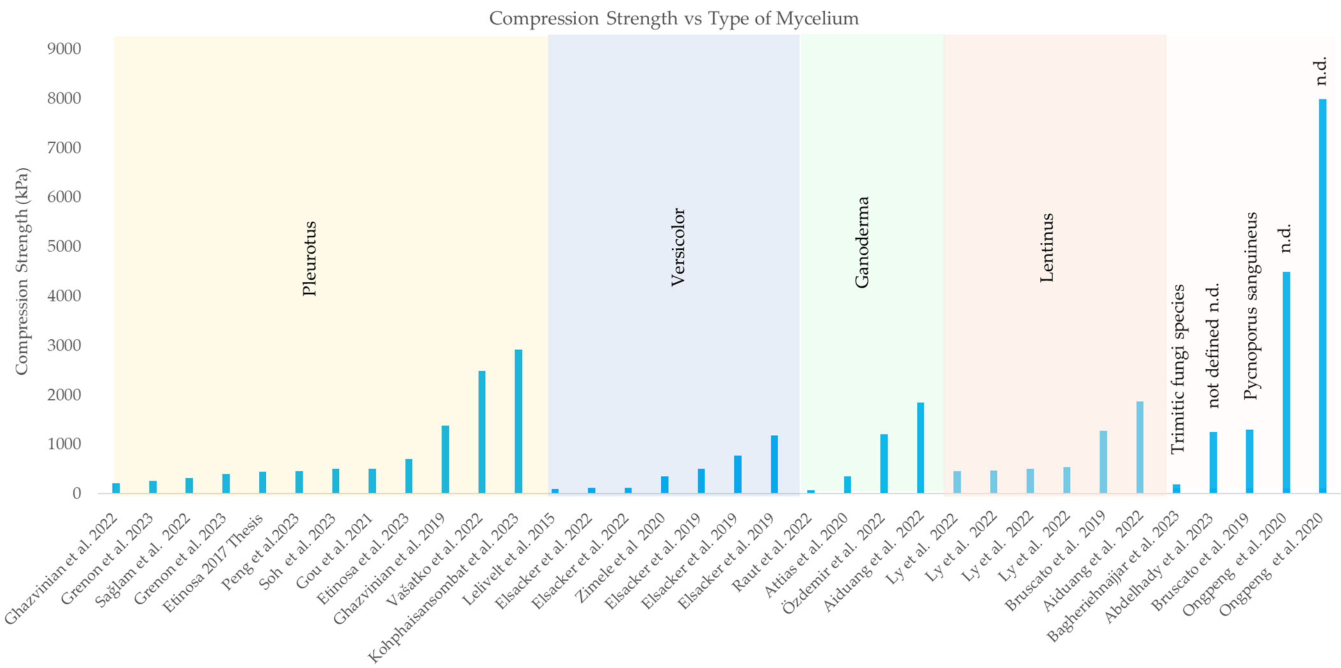

Figure 6. Compression strength per different studies in the literature. Classification of type of mycelium [13,32,34,35,54,57,64,65,68–81].

3.3. Flexural Strength

Tensile, flexural, and impact fractural characteristics are reinforced plastic composites' most commonly investigated mechanical properties. Impact strength is one of the undesirable weak points of these materials regarding mechanical performance. In addition to tensile, flexural, and impact properties, the long-term performance (creep behavior), dynamic mechanical behavior, and compressive properties of NF composites are also investigated. To achieve the desired performance level, significant work is still required, focusing on fiber processing, non-linear behavior, fiber–matrix adhesion, fiber dispersion, and composite manufacturing with optimized processing parameters.

Impact of NFs on the Flexural Strength of FRM

NFs have been widely researched for their impact on the flexural strength of mycelium composites [39,43,66,74,76,80,84,85]. The use of NFs in composite materials has gained attention due to their biodegradability, renewability, and low environmental impact. Many studies have investigated the influence of NFs on the flexural strength of mycelium composites. Adding NFs increases the composite material's flexural strength, acting as reinforcement and inhibiting crack propagation. Furthermore, NF distribution and alignment within the mycelium matrix are critical factors in defining the composite's total flexural strength.

Furthermore, the interaction between NFs and the mycelium matrix has been a focal point of investigation, as it directly impacts the composite's mechanical performance. Understanding the bonding mechanisms and interfacial interactions between NFs and the mycelium matrix is essential for optimizing the composite's flexural strength.

Figure 7 shows the variation of flexural strength values of different FRMs corresponding to the same studies as in the compression results. However, it includes only those that provided data on flexural strength, arranged from the lower values to the high ones. Figures 8 and 9 depict the flexural strength of various FRMs, classified according to the fibrous substrate type and mycelium type, respectively. These visualizations offer insights into how different fibrous substrates and types of mycelium influence the flexural strength of FRMs.

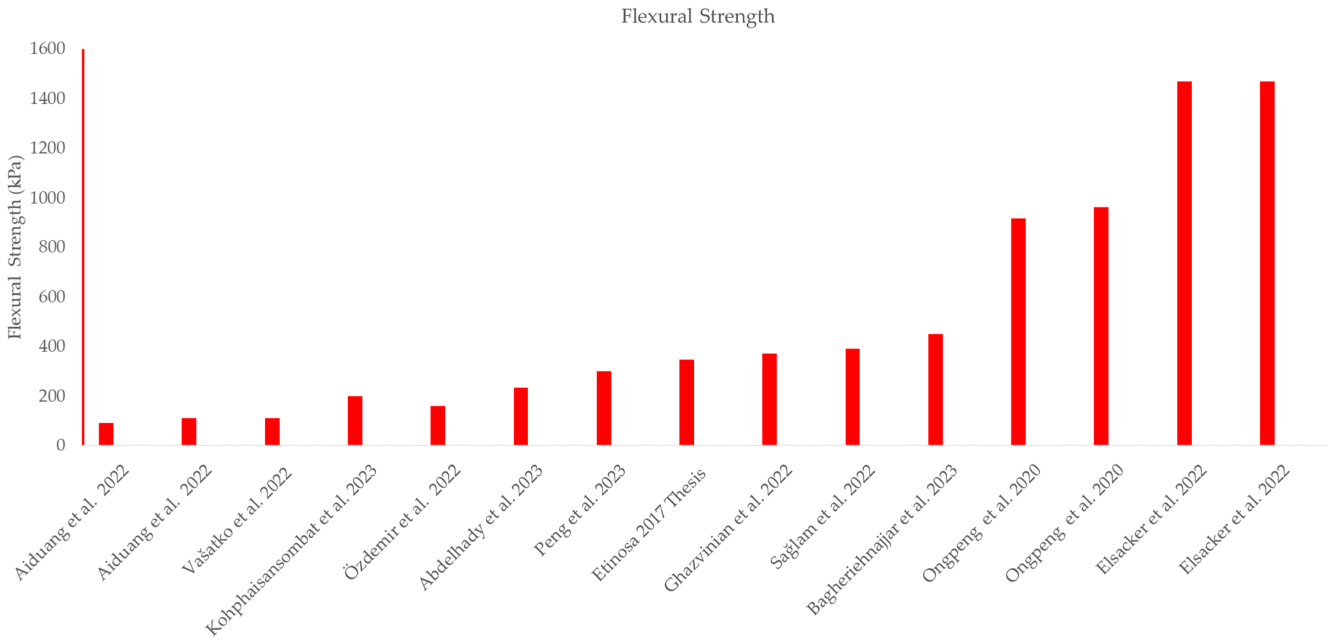

Figure 7. Flexural strength per different studies in the literature [35,54,64,68,71,72,74,76–79,81].

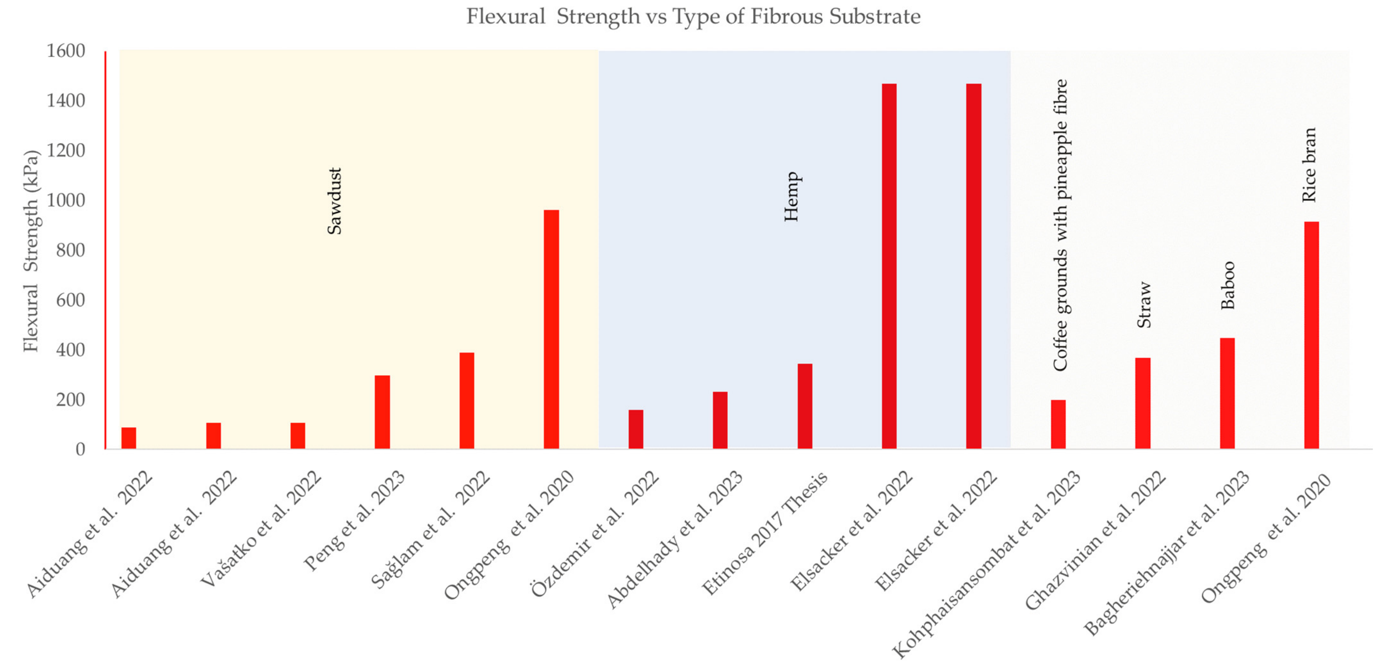

Figure 8. Flexural strength per different studies in the literature. Classification of type of fibrous substrate [35,54,64,68,71,72,74,76–79,81].

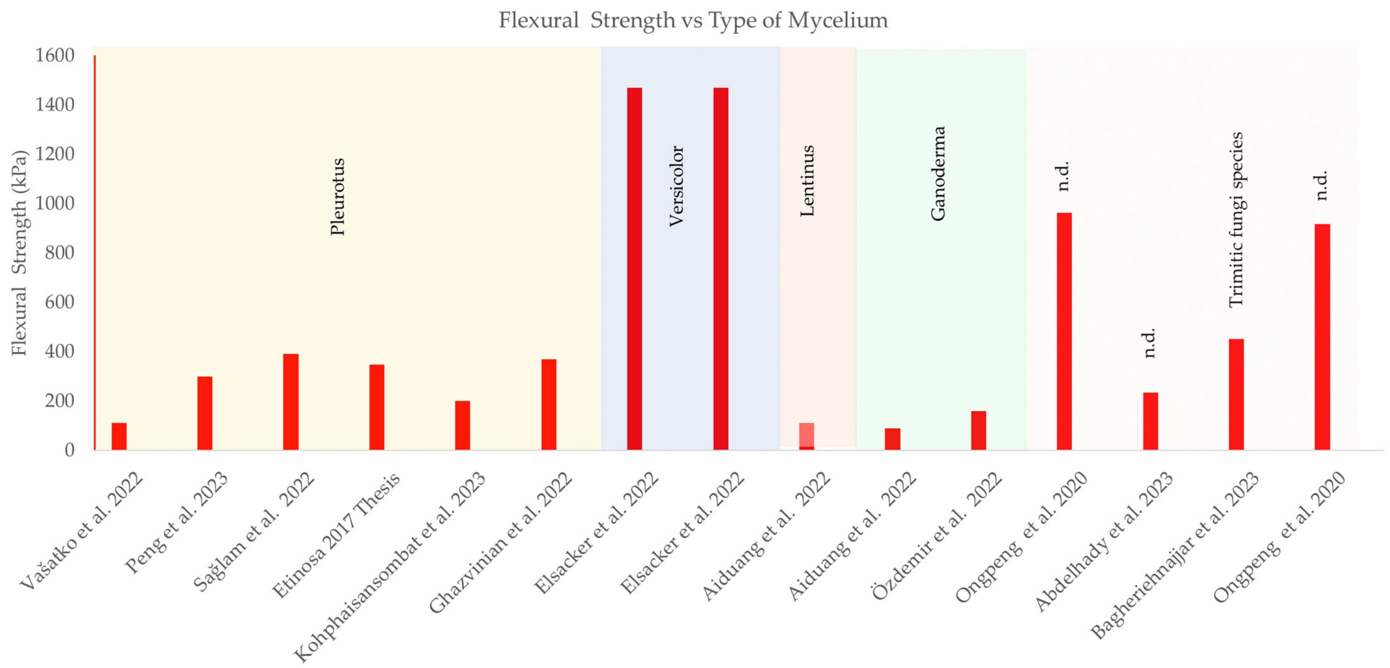

Figure 9. Flexural strength per different studies in the literature. Classification of type of mycelium [32,35,54,68,71,74,76–79,81].

Figure 10 depicts the compressive and flexural strength comparison of various FRMs arranged by groups. It can be seen the optimum combination of high compression and high flexural strength [71].

Incorporating mycelium into brick production, particularly with sawdust and rice bran, significantly enhances compressive strength compared to traditional bricks [71]. Also, the incorporation of mycelium in flexural tests enhances the ductility of brick specimens by reducing crack formation. With increased mycelium content observed in design mixes there is a corresponding increase in linear dimensional change. Microscopic examination reveals the presence of fibers, confirming that natural fibers from mycelium serve as a binding agent in the material.

In addition, the mycelium-based composites with different ratios of natural pineapple fibers exhibit variations in mechanical properties [81]. Figure 11 shows that as the NF content increased, the flexural strength values aligned well with the ranges documented in previous reports. This highlights the positive impact of fiber reinforcement on the composite's mechanical properties. Meanwhile, the compressive strength and density decreased.

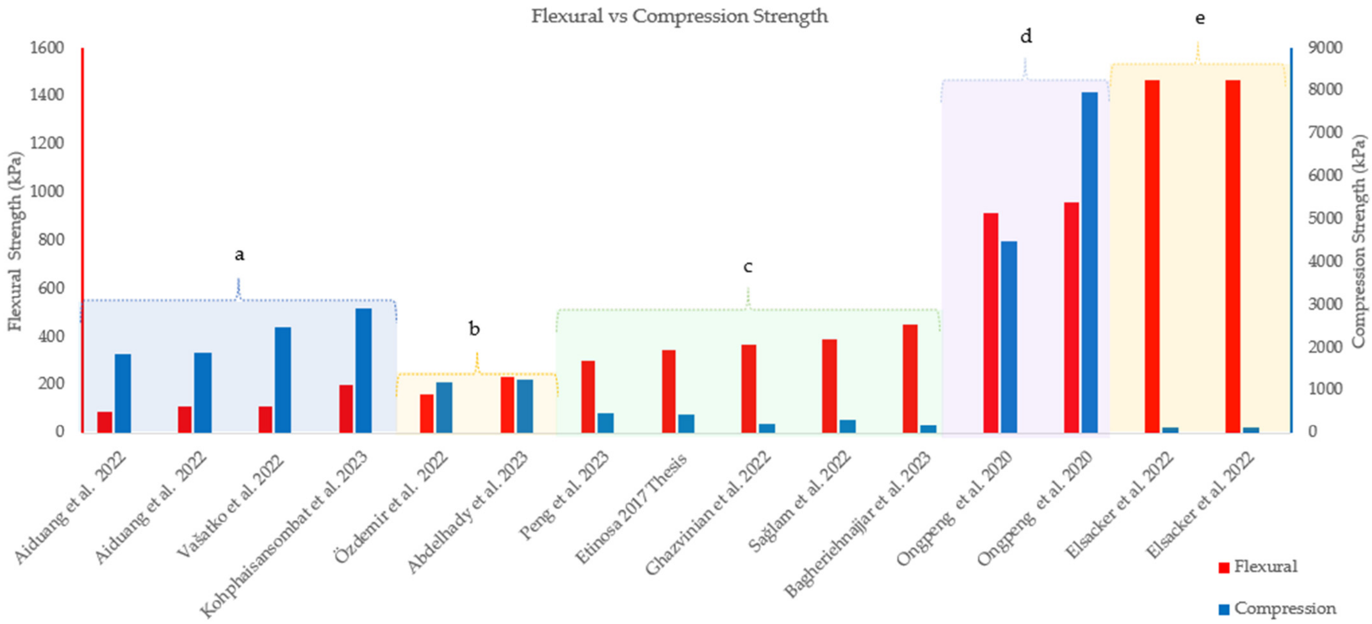

Figure 10. Flexural versus compression strength. There are five subcategories: (a) greater compressive strength than flexural, (b) equal compressive strength than flexural, (c) greater flexural strength than compressive, (d) maximum compressive and flexural strength, (e) maximum flexural and low compressive strength [35,54,64,68,71,72,74,76–79,81].

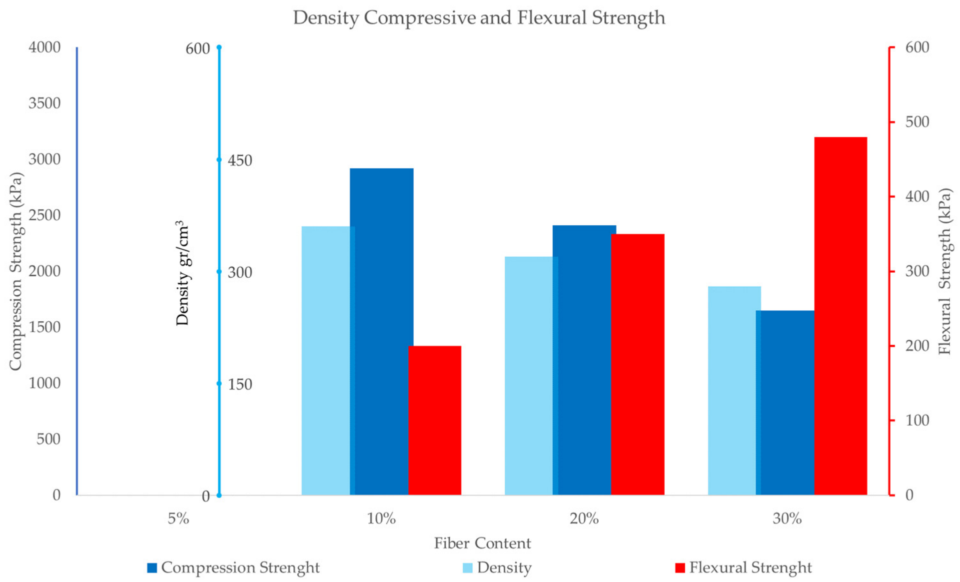

Figure 11. Impact and trend of three different fiber content levels on mechanical properties [81].

Therefore, the incorporation of NFs in mycelium composites significantly influences their flexural strength. Further exploration and understanding of the intricate relationship between NFs and the mycelium matrix will contribute to the development of high-performance, sustainable composites with enhanced flexural strength.

Several factors contribute to the complex relationship between compressive and flexural strength, including material composition, microstructure, and any potential defects or flaws within the material.

Through further exploration of these variables, scientists and engineers can obtain a more thorough comprehension of how these characteristics interact and impact the overall performance of materials under different loading scenarios.

For a number of different possible factors, rice bran with mycelium bricks in the study by Ongpeng et al. had higher flexural strength than other mycelium specimen mix designs [71]. First, rice bran was shown to be a useful substrate for the formation of mycelium. Rice bran's nutrients probably encouraged mycelium growth, strengthening and tightening the brick's fibrous network.

The amount of fiber incorporated into mycelium-based bio-composites significantly influences their flexural strength through various mechanisms. Fibers act as reinforcement, increasing resistance to bending and deformation, and their presence helps distribute stress more evenly across the matrix. Additionally, fibers bridge micro-cracks, preventing their propagation and enhancing strength. The aspect ratio of fibers affects their reinforcing efficiency, with longer fibers relative to their diameter providing better mechanical interlocking. The volume fraction of fibers is critical, as too few fibers may not provide adequate reinforcement, while too many can cause agglomeration and stress concentration, reducing strength. Compatibility between fibers and the mycelium matrix is essential for effective stress transfer, and fiber orientation impacts the direction and magnitude of reinforcement. Maximizing reinforcement without compromising the composite's structural integrity or workability is crucial to achieving an optimal fiber amount. Adding fibers like bamboo increases flexural strength by providing extra support within the matrix, with fine fibers ensuring even distribution and improved binding to the mycelium, thereby enhancing structural integrity. A uniform composite, achieved through the consistent distribution of mycelium and reinforcing materials, enhances flexural strength by evenly absorbing and dissipating stress. Furthermore, the chemical and physical bonds between the mycelium matrix and added fibers or substrates significantly influence the composite's capacity to withstand flexural forces [35].

The type of mycelium has a crucial effect on the flexural strength of the FRM composite. In addition to all the above factors, Pleurotus ostreatus is the optimum type. The distribution of flexural strength among similar mycelium types from the literature can be seen in Figure 9.

4. Discussion—Setbacks and Future

The existing literature highlights mycelium composites' potential in architectural and civil engineering due to their sustainability and eco-friendliness. It emphasizes the importance of substrate selection, type of mycelium, and other variables that highly influence the structural behavior in the final product and how the NFs can enhance mechanical properties.

The MBCs produced from corn husk exhibited the highest flexural strength values, followed by MBCs produced from rice straw and sawdust, respectively. The exact values spanned a range from 0.05 to 4.40 MPa, indicating a notable variation in flexural strength that depended on the fibrous substrate used in the production of the composites. Furthermore, the sawdust substrate presents higher compression strength values in different types of mycelium. While the corn husk exhibits higher flexural strength for the same type of mycelium, the experimental results highlight that factors such as the type of substrate and the fungal species influence both compressive and flexural strengths. Therefore, these materials can be tailored for specific mechanical properties by adjusting these variables, which opens up their potential use in various sustainable construction applications [77].

The major obstacles to the broader application of mycelium composites in architectural and civil engineering are the need for legal design codes, standardized detailing practices, limited ductility, insufficient information on fire and durability performance, and the absence of simplified design manuals for structural engineers. Mycelium composites show great promise in architectural and civil engineering due to their eco-friendliness, lightweight durability, and versatility in shaping. However, their wider application faces challenges such as the lack of standardized testing methods and building codes, which creates uncertainties about their long-term performance. Scalability of production is also a significant issue, as current small-scale methods cannot meet the demands of larger projects. Further research is needed to improve mechanical properties and fire resistance. Collaboration among researchers, industry professionals, and regulatory bodies is crucial to establishing guidelines, conducting testing, and driving innovation, allowing mycelium composites to transform the industry.

For comparison reasons, as shown in Table 2, the sawdust substrate presents higher compression strength values in different types of fungal, while the corn husk exhibits higher flexural strength for the same type of fungal. To conclude, the type of substrate is a crucial factor for the mechanical properties. No unique type of substrate optimally enhances both compression and flexural strength simultaneously.

Table 2. Compression and flexural strength for different substrates and fungal species [77].

Substrates	Fungal Species	Compression Strength * (MPa)	Flexural Strength * (MPa)
Sawdust	*Ganoderma fornicatum*	1.71 ± 0.03 b	0.07 ± 0.00 bc
	Ganoderma williamsianum	1.85 ± 0.01 a	0.09 ± 0.02 ab
	Lentinus sajor-caju	1.87 ± 0.03 a	0.11 ± 0.02 a
	Schizophyllum commune	1.59 ± 0.02 c	0.06 ± 0.01 c
Corn husk	*Ganoderma fornicatum*	0.59 ± 0.01 b	0.19 ± 0.01 b
	Ganoderma williamsianum	0.62 ± 0.01 a	0.28 ± 0.03 a
	Lentinus sajor-caju	0.62 ± 0.02 a	0.32 ± 0.02 a
	Schizophyllum commune	0.58 ± 0.02 b	0.18 ± 0.04 b
Rice straw	*Ganoderma fornicatum*	0.33 ± 0.01 a	0.10 ± 0.02 b
	Ganoderma williamsianum	0.36 ± 0.02 a	0.15 ± 0.03 a
	Lentinus sajor-caju	0.33 ± 0.04 a	0.16 ± 0.02 a
	Schizophyllum commune	0.25 ± 0.03 b	0.07 ± 0.01 b

* The results are mean ± standard deviation. Different letters in the same column in each substrate type are considered significantly different according to Duncan's multiple range test ($p \leq 0.05$).

While mycelium composites offer significant sustainability benefits, including low cost, low density, low energy consumption, minimal carbon emissions, and biodegradability, their structural limitations deserve consideration. However, because it is a relatively new material, there are currently no established scientific standard protocols.

When mycelium composites are exposed to soil environments, they degrade over time. The decomposition rate depends on factors such as material composition, production method, and characteristics associated with the degradation process [84]. Additionally, further research is needed to understand the complexities of the degradation process and its implications for long-term sustainability.

5. Conclusions

FRM composites offer a sustainable alternative to traditional materials with their customizable mechanical properties, particularly in compression and flexural strength. The enhancements in natural FRM composites with NFs focus on improving their mechanical properties, mainly their compressive and flexural strength, which are crucial for various construction applications. The ability to modify these properties through the choice of reinforcement NFs and composite design highlights the versatility and potential of mycelium-based materials in sustainable building construction materials.

- Despite the extensive research on NF treatments and substrate modifications with known materials, the literature does not clearly demonstrate an easy method to enhance the mechanical properties of mycelium composites. The primary reason for this is the complex, multifactorial nature of the type of mycelium and the type of fibrous substrate.
- Mycelium materials differ from traditional fiber composites as they are fully biological, sustainable, biodegradable, and have lower environmental impact. The mix proportion in mycelium materials, containing hyphae, is not precisely known initially, unlike traditional composites. FRM composites provide a sustainable alternative to traditional materials, offering customizable mechanical properties, especially in compression and flexural strength.
- Factors like porosity, fillers and reinforcements influence the relationship between density and compressive strength in mycelium bio-composites. Higher density from high-strength reinforcements can significantly increase the composite's compressive strength. Adjustments in the ratio of reinforcing fibers can lead to more robust FRM composites with higher compressive strength values compared to other studies using different techniques or materials.
- The addition of an optimized quantity of NFs to FRMs positively impacts their flexural strength.
- Utilizing simulation and machine learning tools can help understand and predict optimal adhesive properties in mycelium-based materials, enhancing their application in various fields, including the construction realm.
- The development of standardized design codes for mycelium composites would not only facilitate their widespread adoption but also pave the way for innovative and eco-friendly structural solutions.

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Nomenclature

NF	Natural Fiber
FRM	Fiber-Reinforced Mycelium
MBCs	Mycelium-based Bio-Composites

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