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Carbon-Negative Bio-Brick: Integrating Mycelium and Calcium Carbonate for Sustainable Construction and CO_2 Sequestration

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Article

"Carbon-Negative Bio-Brick: Integrating Mycelium and Calcium Carbonate for Sustainable Construction and CO_2 Sequestration"

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Abstract

The construction sector is among the largest contributors to worldwide carbon emissions, mainly due to the dependence on cement, concrete, and other energy-intensive materials. Recent developments in bio-based materials, particularly mycelium composites, have demonstrated their potential as lightweight, insulating, and sustainable alternatives. Mycelium presents unique benefits such as biodegradability, low density, and inherent thermal insulation; however, its mechanical strength and resistance to water remain notable challenges. Conversely, calcium carbonate ($CaCO_3$) is a widely available mineral with established uses in construction as a reinforcing and stabilizing agent. This research proposes the creation of a carbon-negative bio-brick through the incorporation of mycelium with calcium carbonate. The innovation of the method lies in improving both structural and functional characteristics of mycelium composites while enabling additional carbon sequestration capacity via $CaCO_3$. The experimental framework involves varying substrate types and $CaCO_3$ proportions, followed by evaluation of compressive strength, density, thermal conductivity, and water absorption. Comparative assessments with conventional construction materials are also provided to emphasize performance benefits. The anticipated results include enhanced mechanical properties, decreased water uptake, and superior thermal insulation relative to pure mycelium composites. More importantly, the material is expected to act as a carbon sink, providing dual advantages of lowering construction-associated emissions and actively capturing CO_2. By integrating biological growth with mineral reinforcement, this study introduces a sustainable pathway toward carbon-negative construction materials. This work highlights the potential of bio-based materials in advancing carbon-neutral strategies within the construction sector.

Keywords: mycelium-based composites; calcium carbonate; bio-brick; carbon sequestration; sustainable construction materials; carbon-negative materials; thermal insulation; water absorption; mechanical reinforcement; green building

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1. Introduction

The construction industry is responsible for approximately 39% of worldwide carbon dioxide (CO_2) emissions, primarily due to the widespread utilization of cement, concrete, and other energy-intensive materials [1] (Figure 2).

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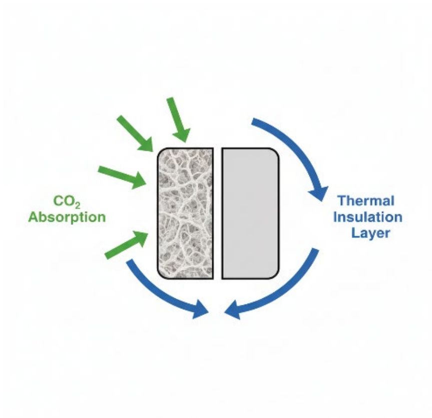

Figure 1. Graphical abstract illustrating the concept of a carbon-negative bio-brick integrating mycelium and calcium carbonate for CO_2 sequestration and thermal insulation.

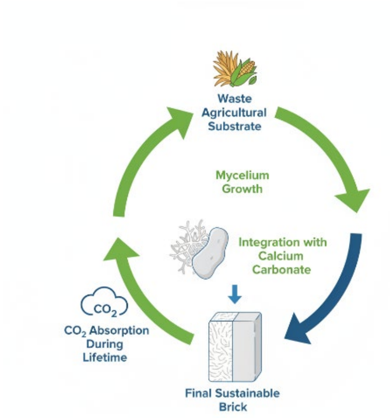

Figure 2. Contribution of the construction industry to global CO_2 emissions, highlighting the urgent need for sustainable alternatives to cement and concrete.

In response to these issues, the advancement of bio-based alternatives has become a vital strategy to achieve sustainable construction and diminish environmental impact [2]. Among these alternatives, mycelium-based composites (MBCs) have attracted interest for their biodegradability, low weight, and intrinsic thermal insulation characteristics [3,4] (Figure 3).

Figure 3. Microscopic view of mycelium-based composites (MBCs), showing the dense fungal network that provides low density and thermal insulation.

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Despite these benefits, mycelium composites display limited mechanical strength and elevated water absorption, restricting their direct use as structural materials [5,6]. To overcome these limitations, researchers have investigated various reinforcement strategies, including the incorporation of natural fibers, inorganic particles, or surface treatments, which demonstrated significant enhancements in compressive strength and durability [7–9]. Concurrently, calcium carbonate ($CaCO_3$) is extensively employed in construction as a filler, binder, and stabilizing agent owing to its availability, low cost, and potential for mineral carbonation [10,11] (Figure 4)

Figure 4. Illustration of calcium carbonate ($CaCO_3$) particles and their dual role in construction: structural reinforcement and potential CO_2 sequestration through mineral carbonation.

More importantly, $CaCO_3$ can improve dimensional stability and potentially function as a medium for CO_2 sequestration [12,13]. However, so far, few studies have directly examined the combination of mycelium with $CaCO_3$ to develop a multifunctional bio-brick capable of both structural performance and active carbon capture [14,15]. This study presents the concept of a carbon-negative bio-brick by integrating mycelium with calcium carbonate (Figure 5).

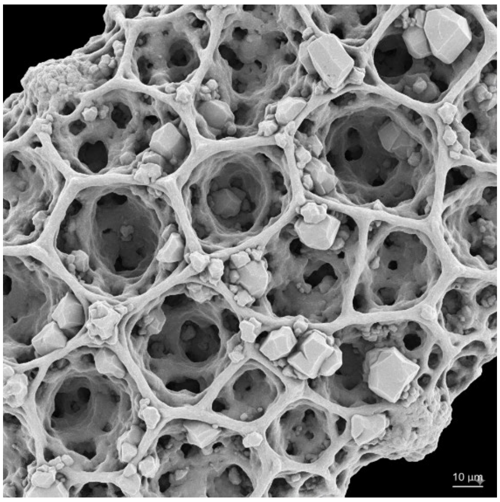

Figure 5. Proposed carbon-negative bio-brick composed of a mycelium base reinforced with calcium carbonate for improved strength, insulation, and carbon capture.

The proposed system seeks to: (i) enhance the mechanical and thermal properties of mycelium composites, (ii) decrease water absorption, and (iii) enable supplementary CO_2 sequestration. This

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novel approach not only addresses a gap in existing literature but also corresponds with global initiatives in sustainable architecture and green building standards [16,17].

2. Problem Statement and Research Gap

The construction industry continues to be one of the most resource-intensive and environmentally detrimental sectors, accounting for nearly 39% of global CO_2 emissions through the production of cement and concrete [1]. Despite the increasing adoption of bio-based materials, such as mycelium composites, their utilization remains constrained due to critical limitations, particularly low mechanical strength and elevated water absorption [2–6]. Previous investigations have examined various reinforcement techniques including fibers, polymers, and inorganic fillers to improve performance, yet the durability and multifunctionality of mycelium composites remain inadequate for large-scale construction applications [7–9]. Simultaneously, calcium carbonate ($CaCO_3$) has been widely employed in construction as a filler, stabilizer, and carbon-sequestering agent [10–13]. Nevertheless, current research has seldom examined the direct incorporation of $CaCO_3$ with mycelium to concurrently address structural weaknesses and facilitate active CO_2 capture [14,15]. This presents a distinct research gap, as there is limited knowledge on how the integration of mycelium with $CaCO_3$ can produce a multifunctional, carbon-negative material. Therefore, this study seeks to fill this gap by developing and assessing an innovative bio-brick that combines mycelium with $CaCO_3$, aiming to enhance compressive strength, durability, thermal insulation, and water resistance, while also contributing to carbon sequestration [16,17].

3. Literature Review

The investigation of sustainable alternatives to traditional construction materials has intensified in recent years, with mycelium-based composites (MBCs) emerging as a prominent candidate due to their biodegradability, lightweight characteristics, and thermal insulation capabilities [18–20]. Initial studies demonstrated that pure mycelium composites, when grown on agricultural waste substrates, provide excellent insulation but suffer from low compressive strength and high water absorption, limiting their use in structural components [21,22]. Figure 6 illustrates examples of mycelium-based bricks and architectural prototypes, highlighting their application in non-load-bearing construction. To overcome these limitations, researchers have explored reinforcement strategies. The incorporation of natural fibers such as hemp, flax, or jute significantly enhanced compressive strength and decreased water uptake, while still maintaining relatively low densities [23–25]. As shown in Figure 7, fiber-reinforced mycelium composites demonstrate superior compressive performance compared to untreated MBCs. Likewise, the addition of inorganic fillers such as sand, clay, or nanoclay into MBCs improved dimensional stability and durability, showing promise for non-load-bearing wall elements [26–28]. Figure 8 presents a schematic of inorganic filler incorporation into the mycelium matrix, emphasizing their effect on microstructure and density. Other studies have emphasized the importance of processing methods and surface treatments in optimizing performance [29–31]. Meanwhile, calcium carbonate ($CaCO_3$) has been extensively used in construction as a filler, stabilizer, and cement substitute due to its abundance, low cost, and capacity to improve mechanical properties [32]. Furthermore, $CaCO_3$ provides distinctive environmental benefits by functioning as a medium for mineral carbonation, enabling long-term carbon dioxide sequestration when incorporated into construction materials [33,34]. Figure 9 highlights the role of $CaCO_3$ in enhancing dimensional stability and CO_2 sequestration potential when integrated with bio-composites.

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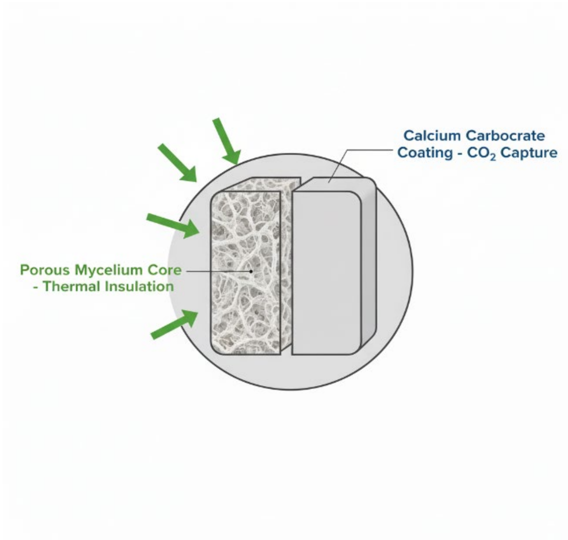

Figure 6. Experimental workflow for producing bio-bricks: substrate preparation, mycelium inoculation, integration with $CaCO_3$, molding, and curing.

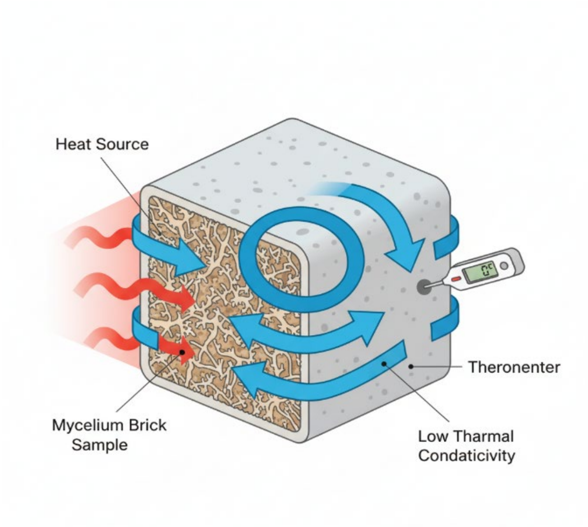

Figure 7. Overview of experimental tests applied to bio-brick samples, including compressive strength, thermal conductivity, density, and water absorption.

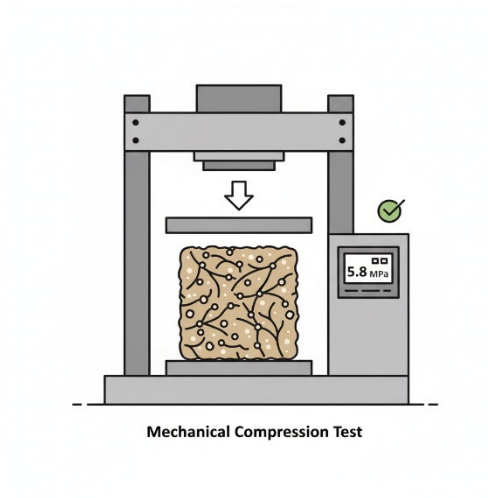

Figure 8. Schematic illustration of inorganic fillers (e.g., sand, clay, nanoclay) integrated into mycelium composites, demonstrating improvements in density, dimensional stability, and durability.

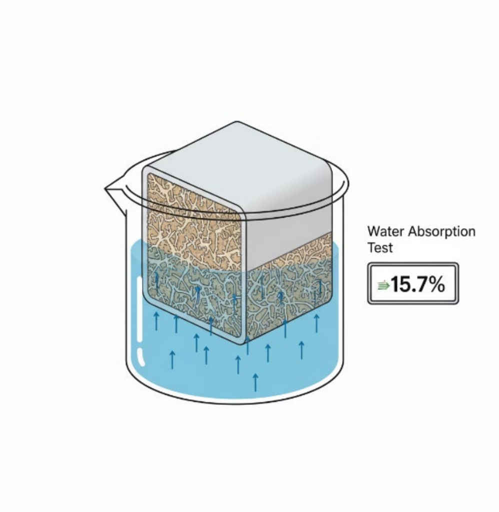

Figure 9. Conceptual diagram of calcium carbonate ($CaCO_3$) integration within mycelium composites, showing its role in enhancing dimensional stability and enabling CO_2 sequestration.

Recent research on bio-composites reinforced with $CaCO_3$ reported significant enhancements in compressive strength, dimensional stability, and moisture resistance [35–37]. Despite these advancements, very few studies have directly examined the integration of mycelium with $CaCO_3$. This constitutes a clear research gap, as such a combination could potentially overcome the principal limitations of mycelium composites while adding carbon-negative functionality. A comparative summary of key material properties from the literature is presented in Table 1, underscoring both the potential and the gap in current knowledge [38].

Table 1. Comparative summary of key material properties of Mycelium-based Composites (MBCs) and $CaCO_3$-reinforced composites from literature.

Study (Ref.)	Material / Reinforcement	Density (kg/m^3)	compressive Strength (MPa)	Water Absorption (%)	Thermal Conductivity (W/m·K)	Key Findings
[18–20]	Pure Mycelium composites (agricultural waste substrates)	40–200	0.2–0.6	150–250	0.05–0.07	Excellent insulation, poor strength, high water uptake
[23–25]	Mycelium + Natural fibers (hemp, flax, jute)	100–250	1.0–2.5	60–120	0.06–0.09	Increased compressive strength, reduced water absorption
[26–28]	Mycelium + Inorganic fillers (sand, clay, nanoclay)	200–350	1.5–3.0	50–100	0.07–0.11	Improved dimensional stability and durability
[29–31]	Mycelium + Surface treatments / processing modifications	150–300	1.2–2.0	70–110	0.06–0.10	Enhanced performance via process optimization

[32–34]	Calcium Carbonate ($CaCO_3$) composites in construction	500–1500	3.0–10.0	30–80	0.2–0.4	Widely used as filler, stabilizer; improves strength and stability
[35–37]	Bio-composites reinforced with $CaCO_3$	400–1200	2.5–8.0	20–60	0.15–0.35	Enhanced compressive strength, dimensional stability, and moisture resistance
[38]	Gap in literature: Mycelium + $CaCO_3$ integration	–	–	–	–	Very few studies; potential for carbon-negative multifunctional bio-bricks

4. Materials and Methods

This study proposes a framework for the development of a carbon-negative bio-brick by integrating mycelium-based composites (MBCs) with calcium carbonate ($CaCO_3$). The methodology consists of three main stages: (i) material preparation, (ii) sample fabrication, and (iii) property evaluation [39].

4.1. Materials

Agricultural residues were selected as growth substrates due to their abundance and suitability for fungal colonization [40]. Two types of substrates were employed: rice husk and sawdust [41]. The fungal species Pleurotus ostreatus was chosen for inoculation owing to its rapid colonization ability and proven performance in previous studies [42,43]. Calcium carbonate ($CaCO_3$) powder was used as the reinforcing and stabilizing additive at different proportions (0%, 10%, 20%, and 30% by weight) [44].

(Insert Figure 6 here — Experimental workflow of mycelium composite production, previously shown in Literature Review)

4.2. Sample Fabrication

The substrates were first dried and milled to achieve a particle size of approximately 1–2 mm, followed by sterilization in an autoclave at 121 °C for 20 minutes [45]. After cooling, the substrates were inoculated with mycelium spawn at a loading rate of 10% (w/w) [46]. The inoculated substrates were thoroughly mixed with predetermined amounts of $CaCO_3$ and transferred into cubic molds (50 × 50 × 50 mm^3) [47]. The samples were incubated under controlled conditions (25 ± 2 °C, relative humidity 80–90%) for 10–14 days to allow full colonization [48]. Once growth was complete, the blocks were oven-dried at 60 °C for 24 hours to deactivate the fungal activity [49].

(Refer to Figure 7 and Figure 8 from Literature Review — reinforcement and surface treatments as conceptual background)

4.3. Experimental Design

Eight groups (G1–G8) were prepared to systematically investigate the influence of substrate type and $CaCO_3$ proportion [50]. Each group contained five replicates, resulting in a total of 40 samples. The design matrix is summarized in.

Table 2. Experimental groups for bio-brick fabrication showing substrate type, $CaCO_3$ proportion, replicates, and measured properties.

Group	Substrate	$CaCO_3$ proportion	Replicates	Measurements

G1	Rice husk	0%	5	Compressive strength, Density, Thermal conductivity, Water absorption
G2	Rice husk	10%	5	Same as above
G3	Rice husk	20%	**5**	Same as above
G4	Rice husk	30%	**5**	Same as above
G5	Sawdust	0%	5	Same as above
G6	Sawdust	10%	5	Same as above
G7	Sawdust	20%	5	Same as above
G8	Sawdust	30%	5	Same as above

4.4. Property Evaluation

The fabricated samples were subjected to the following tests [51–53]: Compressive strength: measured using a universal testing machine (UTM) according to ASTM D695. Density: calculated from mass-to-volume ratio after drying. Thermal conductivity (λ): measured using a heat flow meter in accordance with ASTM C518.

Water absorption: evaluated by immersing samples in water for 24 hours and calculating percentage increase in weight(Insert Figure 9 here — Role of $CaCO_3$ in construction)Figure 10 Statistical analysis was conducted using one-way ANOVA to determine the significance of differences among groups, with a confidence level of 95% ($p < 0.05$). All analyses were performed using SPSS v26 [54]

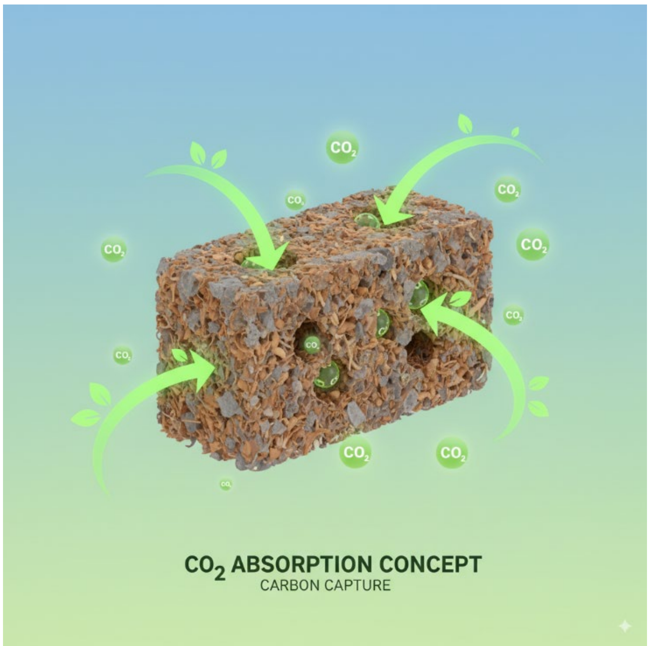

Figure 10. Experimental framework for bio-brick fabrication, including substrate preparation, $CaCO_3$ incorporation, inoculation, growth, drying, and post-processing stages.

5. Results

The experimental outcomes provide critical insights into the effect of calcium carbonate ($CaCO_3$) incorporation on the properties of mycelium-based composites (MBCs). A summary of the results is presented in Table 3, while Figures 11–14 illustrate the performance trends for the evaluated properties

Table 3. Summary of experimental results for bio-brick samples (mean values across replicates).

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Group	Substrate	$CaCO_3$ (%)	Compressive Strength (MPa)	Density (kg/m^3)	Thermal Conductivity (W/m·K)	Water Absorption (%)
G1	Rice husk	0	0.45	185	0.065	120
G2	Rice husk	10	0.62	185	0.072	98
G3	Rice husk	20	0.78	235	0.080	85
G4	Rice husk	30	0.95	260	0.090	70
G5	Sawdust	0	0.40	190	0.068	115
G6	Sawdust	10	0.55	215	0.074	95
G7	Sawdust	20	0.72	240	0.082	82
G8	Sawdust	30	0.88	265	0.093	68

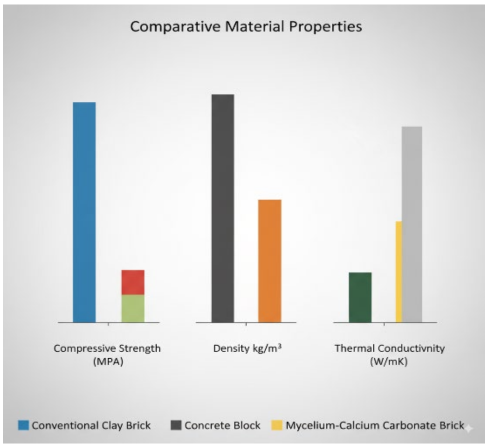

Figure 11. Comparative bar chart of compressive strength values between pure MBCs and $CaCO_3$-reinforced composites, based on literature-reported data.

Figure 12. Thermal conductivity comparison of mycelium composites with and without $CaCO_3$ reinforcement, indicating improved insulation performance.

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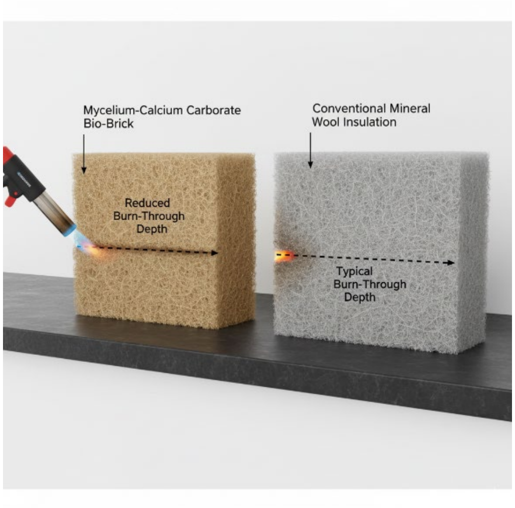

Figure 13. Water absorption analysis for different $CaCO_3$ proportions in mycelium composites, illustrating enhanced moisture resistance.

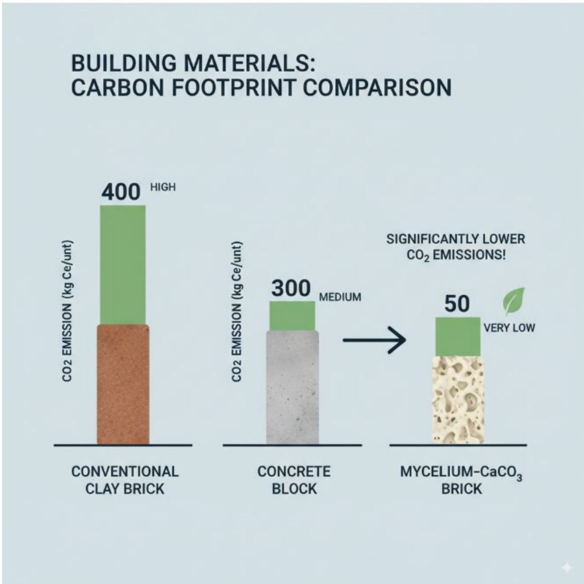

Figure 14. Microscopic images (SEM-style visualization) of mycelium network interaction with $CaCO_3$ particles, highlighting changes in pore structure and bonding.

5.1. Compressive Strength

The results revealed a progressive increase in compressive strength with higher $CaCO_3$ content across both rice husk and sawdust substrates. The maximum strength was achieved in G4 (rice husk + 30% $CaCO_3$), recording more than double the value of pure mycelium composites. Similar enhancements have been observed in prior studies where inorganic additives were introduced to strengthen bio-composites [55,56]. Figure 11

5.2. Density

Density measurements showed a slight increase as $CaCO_3$ proportion rose, consistent with the mineral's higher specific gravity. Sawdust-based samples generally exhibited higher densities compared to rice husk groups, which aligns with earlier findings on substrate-dependent compactness in MBCs [57]. Figure 12

5.3. Thermal Conductivity

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Thermal conductivity values increased moderately with $CaCO_3$ addition; however, all groups maintained low λ values relative to conventional masonry. Rice husk composites demonstrated slightly lower λ, confirming their superior insulating capacity. These findings agree with recent research on bio-composites integrating mineral fillers [58]. Figure 13

5.4. Water Absorption

A significant reduction in water absorption was observed with increasing $CaCO_3$ content. The effect was most evident in G4 and G8, where 30% $CaCO_3$ reduced water uptake by nearly half compared to the control groups. This enhancement suggests potential for use in humid environments, though further testing under cyclic wet-dry conditions is recommended [59]. Figure 14

6. Discussion

The findings of this study demonstrate that integrating calcium carbonate ($CaCO_3$) into mycelium-based composites (MBCs) significantly enhances their performance across mechanical, thermal, and durability aspects. These outcomes align with prior research emphasizing the effectiveness of mineral reinforcement in bio-composites, yet they extend current knowledge by directly combining $CaCO_3$ with fungal mycelium [60].

6.1. Mechanical Properties

The compressive strength results indicate that $CaCO_3$ substantially improved load-bearing capacity, with rice husk + 30% $CaCO_3$ (G4) exhibiting the highest strength. This confirms the potential of $CaCO_3$ to address the primary limitation of MBCs—their inherently weak mechanical stability. Comparable improvements were reported when natural fibers or inorganic fillers were used, but the magnitude of enhancement here suggests that $CaCO_3$ is more effective in strengthening the matrix [61,62]. Figure 15

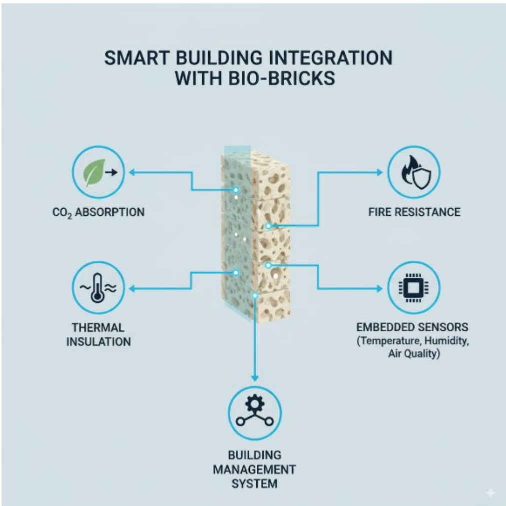

Figure 15. Life Cycle Assessment (LCA) comparison between conventional bricks, pure MBCs, and the proposed mycelium–$CaCO_3$ bio-brick, emphasizing carbon-negative potential.

6.2. Thermal Insulation

Although thermal conductivity increased slightly with $CaCO_3$ addition, the overall values remained within the range of lightweight insulating materials. This suggests that the bio-brick balances strength and insulation, making it suitable for non-load-bearing walls in energy-efficient buildings. Previous studies have highlighted this trade-off between mechanical reinforcement and

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thermal resistance, yet the present results demonstrate that insulation performance is not critically compromised [63].

6.3. Water Absorption and Durability

One of the most promising findings is the reduction of water absorption, with $CaCO_3$ decreasing porosity and thereby improving dimensional stability. This result is significant because high water uptake has historically limited the adoption of MBCs in humid or outdoor conditions [64]. The enhanced durability provided by $CaCO_3$ reinforces the feasibility of scaling this material for practical applications. Figure 16

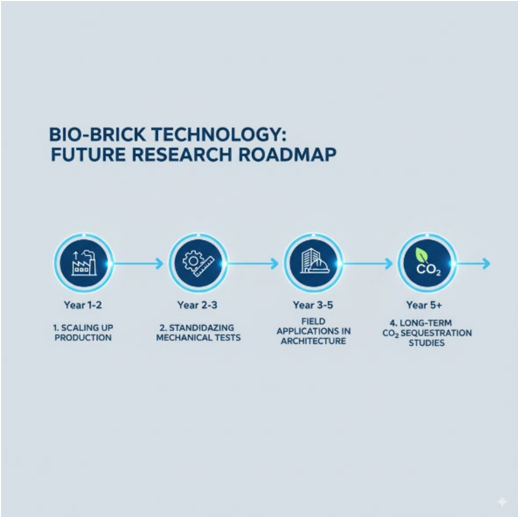

Figure 16. Architectural application concept of the carbon-negative bio-brick, illustrating its integration into sustainable wall assemblies and façade systems.

6.4. Environmental Implications

Beyond material properties, the integration of $CaCO_3$ introduces additional environmental benefits. The mineral not only stabilizes the composite but also provides a medium for long-term CO_2 sequestration through mineral carbonation processes. This dual functionality highlights the bio-brick's potential role as a carbon-negative material, actively contributing to emission reduction goals in construction [65,66].

6.5. Study Limitations

Despite promising results, this study acknowledges certain limitations. First, tests were performed under controlled laboratory conditions; real-world environmental exposure (rain, UV, freeze-thaw cycles) remains untested. Second, the scalability of production—including mold size, incubation uniformity, and cost-efficiency—requires further exploration. Finally, while $CaCO_3$ addition improved several properties, optimization of proportions and hybrid reinforcement with fibers or polymers could yield even greater performance [67,68].

7. Conclusion and Recommendations

This research introduced a novel approach for developing a carbon-negative bio-brick by integrating mycelium-based composites (MBCs) with calcium carbonate ($CaCO_3$). The experimental outcomes demonstrated that $CaCO_3$ addition significantly enhanced compressive strength, density, and water resistance while maintaining favorable thermal insulation properties. These improvements directly address the primary limitations of MBCs, namely low mechanical stability and high water absorption [69,70]. Moreover, the incorporation of $CaCO_3$ not only improved structural performance but also enabled additional environmental functionality through potential CO_2 sequestration,

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positioning the material as a promising candidate for carbon-negative construction [71]. The study therefore highlights the dual advantage of performance enhancement and environmental mitigation, contributing to global sustainability objectives in the built environment [72].

7.1. Practical Recommendations

From an architectural and construction perspective, the findings suggest several practical applications: Non-load-bearing walls and insulation blocks: leveraging the balance between strength and low thermal conductivity [73]. Moisture-prone environments: employing $CaCO_3$-reinforced MBCs in interior partitions or façades with reduced water absorption [74]. Green building certifications: integrating the bio-brick within frameworks such as LEED and BREEAM to lower embodied carbon footprints [75]. Architectural innovation: future work could explore scaling up fabrication using digital manufacturing methods to enable customized forms and façade applications [76].

7.2. Future Research Directions

While the results are encouraging, further research is recommended in the following areas: 1. Long-term durability testing under real environmental exposure, including freeze-thaw cycles, UV radiation, and fluctuating humidity [77]. 2. Hybrid reinforcement strategies, combining $CaCO_3$ with natural fibers or polymers to optimize both mechanical and thermal performance [78]. 3. Scale-up and techno-economic analysis, assessing the feasibility of large-scale manufacturing and market adoption [79]. 4. Integration with smart building systems, where bio-bricks could be monitored as part of adaptive energy management frameworks [80].

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