

Original Article

Develop Process Property Relationships in the Mycelium Composite Block of Paper Pulp and Pleurotus Ostreatus

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Abstract - This study of paper pulp-based Mycelium Composite Blocks developed using the Fungus *Pleurotus Ostreatus* establishes a process-property interrelationship framework to know a reproducible processing range for developing scalable bio-based components. A four-factor experimental design was used to control substrate moisture percentage, spawn loading, incubation temperature, and growth duration, while keeping other pulp preparation process parameters constant, such as particle size, sterilization time and temperature, relative humidity, and deactivation method. Optimum process fabrication parameter identified for substrate and fungi for mycelium growth are pulp-based mycelium composite blocks produced using *Pleurotus Ostreatus*, should be around 60% moisture input, 10% spawn by dry weight of substrate, incubation temperature range 25–28 °C, and around 30 days or before the fruiting body starts developing, which produced uniform colonization and strong interlocking of mycelium. Under these optimum conditions, the mean wet density decreased slightly from $906.9 \pm 110.3 \text{ kg m}^{-3}$ (Day 0) to $867.7 \pm 104.4 \text{ kg m}^{-3}$ (Day 30), indicating slight decomposition of the substratum for mycelial growth. The material exhibited approximately 20% shrinkage after deactivation. Mechanical testing yielded compressive strengths of 2.56 MPa for cylindrical specimens and 2.39 MPa for blocks, which are near the lower compressive strength of burnt clay bricks. Thermal conductivity yielded $\lambda = 0.07 \text{ W/m}\cdot\text{K}$, indicating a moderate insulation category, where increased density improved strength but reduced conductivity.

Keywords - Bio-Based Blocks, Mycelium Composite, Paper Pulp, *Pleurotus Ostreatus*, and Sustainable Materials.

1. Introduction

In light of its significant global emissions and reliance on carbon-neutral materials, the construction industry faces an urgent need to decarbonize. Recent research found that the building industry accounts for around 40% of global carbon emissions, underscoring the need for safer substitutes for conventional building materials and for fossil-fuel-based insulation.[1] In this line, Mycelium-Based Composites (MBCs) have emerged as a promising category of bio-derived alternative materials, in which fungal mycelium can digest and bind lignocellulosic substrates into lightweight, stiff materials, enabling a new approach to circular, low-embodied-energy building components. [2]. MBCs are particularly relevant due to their porous microstructure, which can deliver functional performance in insulation and acoustics in the built environment. Reporting MBC thermal conductivity performance in the range of 0.05–0.07 W/m·K, a range similar to conventional insulation materials. [3]

It also demonstrates strong acoustic absorption compared with standard building panels and polymer foams, which attracts MBCs to use it as interior sound-absorbing elements and envelope components, both for comfort and

sustainability. [4] Even though these advantages exist, the moisture sensitivity, mechanical variability, and energy-intensive processing steps such as sterilization and drying hinder its application as a commercially viable product.[1] Among all available lignocellulosic substrates, recycled paper pulp is attracting attention due to its high cellulose content, availability, and uniform processing, which facilitate mixing, molding, and densification. However, not been explored much in MBC research to develop a block or insulation panel. [3, 5]. *Pleurotus ostreatus* is a pungent fungus for paper-pulp digestion in developing MBCs and is readily available; it grows quickly on lignocellulosic residues, forming dense hyphal networks that bind substrates into solid material and are less moisture-absorbent. [2] These properties of *Pleurotus ostreatus* would help develop scalable MBCs.

Through a literature survey, it is identified that MBC provides low-density, acoustic absorption, and thermal insulation properties which vary widely because final performance is directly dependent on processing parameters, since process controls internal structure such as density, pore morphology, hyphal connectivity, and internal bonding,



which ultimately determine performance. For example, the density of mycelial composites helps describe a multiscale, heterogeneous mycelial network in which lignocellulosic particles are embedded, which, in turn, reflects the strength of MBCs. [2, 6]

Not only mechanical strength, thermal conductivity, and acoustic absorption also depend on internal porosity and airflow resistivity, which is in progress; the voids are filled by mycelium during growth, and as post-processing, it densifies the material. [7, 8]. Critically, many reviews in this research emphasize that the field still struggles with a lack of guidelines, protocols, and standardization, which hinder MBCs' transformation into building products. [1, 9] There is a need for a systematic, data-driven approach to manufacturing factors that interact with fungal strain and morphology, substrate type, environmental growing conditions, molding systems, and post-processing, collectively defining the final properties of MBC in complex ways. [10]

Most published studies have focused on agricultural waste such as rice and wheat straw, hemp, bagasse, and industrial waste sawdust. High cellulose content and urban availability of paper pulp have developed an interest, which has been less examined in the development of Mycelium Composite. *Pleurotus Ostreatus* is an acceptable fungal species for such experimentation for several reasons: it is readily available, has rapid growth, and dense hyphal networks capable of binding lignocellulose substances. Even though there are limited experiments for a reproducible process window for paper-pulp/*Pleurotus Ostreatus* composite blocks, a “process–property” framework for paper pulp and *Pleurotus Ostreatus* composite blocks can be organized into linked stages: first, substrate preparation and conditioning for the growing environment include required hydration, homogenization, and sterilization to reduce contamination risk [11] for *Pleurotus Ostreatus* growth specifically, substrate moisture content and the spawn fraction relative to the dry weight of substrate for a good mycelial network [12, 13]. Secondly, molding, geometry, and material compaction before and during growth can influence density profiles and mechanical response, as compaction reduces air pockets and increases contact between hyphal growth and the lignocellulosic substrate. [6] Next, the Incubation environment for *P. ostreatus* growth includes general parameters such as temperature range and relative humidity, as well as sufficient CO₂, light, and growth span [4]. Lastly, the deactivation and post-processing strongly affect density/porosity and therefore affect mechanical, thermal, and acoustic performance [10]

Accordingly, the research gap addressed in this study is the lack of a process-property paper pulp and *Pleurotus ostreatus* blocks, quantifying specific, controllable process variables and measurable physical and mechanical

properties. The novelty of the work is putting forth four practical fabrication variables most important for mycelium growth: substrate moisture content, spawn loading, incubation temperature, and growth duration, and relating them to MBC properties. Instead of giving proof of fungal colonization only, this study aims to identify an experimentally reproducible processing range for paper-pulp mycelium blocks or non-structural building applications. The absence of a reproducible process window limits the comparability, scalability, and engineering applicability of paper-pulp mycelium composites.[6]

Therefore, the objective of this study is to develop and validate a process–property map for paper pulp–*Pleurotus ostreatus* mycelium composite blocks, identify favorable process conditions, and evaluate the MBC's density, dimensional stability, compressive performance, and thermal conductivity. The broader aim is to provide a systematic link between process and property parameters to develop MBCs into building materials.

2. Literature Review

2.1. Mycelium Composites: Substrates and Reported Ranges

MBCs are typically produced by inoculating a biowaste lignocellulosic substrate with a fungal species whose hyphae grow through the feedstock and act as a natural binder. The reported substrate families are rice/ wheat straws, sawdust, wood shavings, husks, bagasse/coir pith, and mixed agricultural residues, selected primarily based on local availability and desired pore structure. Across the literature, MBCs are repeatedly positioned as lightweight, porous insulation/acoustic materials, with performance ranges comparable to conventional insulators. For example, one insulation-focused review summarizes density 0.02–0.2 g/cm³, thermal conductivity 0.03–0.07 W/m·K, and sound absorption coefficients 0.4–0.9 (about input sound wavelength 500–2000 Hz) [13]. A major reason these ranges spread widely is that substrates strongly affect density and void content. A manufacturing-conditions review reports density ranges of 25–350 kg/m³ for wood-based substrates and 25–437 kg/m³ for agricultural residues [9]. Importantly, paper-pulp and *Pleurotus ostreatus* have been experimented with acoustic-oriented panels, showing clear proof for paper-derived substrates in building products [3].

2.2. Effect of Fungal Species

While many basidiomycetes are used, such as *Ganoderma*, *Trametes*, and *Lentinus*, as a fungal choice, it matters because hyphal morphology, growth rate, resistance to contamination, and bonding behavior influence the final network connectivity and inter-fiber “welding.” Comparative studies frequently selected *Pleurotus ostreatus* species because they are easily available, fast-growing, have lower vulnerability, easy culture conditions, and can grow in non-laboratory production within 15–30 days with an incubation

temperature window of 24–26 °C. This feature of fungi is correlated with fabrication parameters (density, moisture response, strength, thermal conductivity, and acoustics) [14].

2.3. Standard Testing Practices

A recurring issue in MBC literature is that reported properties are difficult to compare across studies because there is no single established testing procedure, and results are highly sensitive to specimen geometry, mould type, porosity gradients, pressing methods, and measurement method. One study stated directly that there is no established testing procedure for MBCs.[9] In thermal testing, transient methods are frequently used for speed but may introduce deviations in highly porous materials, leading to very low conductivities [14]. At the same time, researchers adapted standard methods from the polymer/wood/composite and acoustics fields, using standards for acoustic characterization, including ASTM E1050 and ISO 10534-1/10534-2 for impedance tube sound absorption [15]. Finally, even when similar tests are used, reproducibility is challenged by the number of interacting process variables. Work on improving MBCs emphasizes that achieving consistent physical and mechanical properties remains difficult because outcomes depend on strain choice, substrate type, growth conditions, and manufacturing technique, highlighting the need for systematic, controlled “process windows” and reporting. [16]

2.4. Research Gap Addressed by the Present Study

The reviewed literature shows that the properties of MBC’s are vulnerable to the type of substrate and fungal species, growth condition, mold geometry, and post-processing techniques. It also shows insufficient evidence linking process and property in a single experimental framework, variables such as moisture content, spawn loading, incubation temperature, growth duration, shrinkage, compressive strength, and thermal conductivity. The present study addresses this gap of developing a process-property relationship for waste paper-pulp and *Pleurotus ostreatus* composite blocks observed against findings reported earlier for other mycelium composites.

3. Materials and Methods

3.1. Materials

All the material procured was locally available. A paper pulp substrate was prepared from waste post-consumer office paper, collected and cleaned by removing staples and any plastic, then soaked in potable water for 1 day and manually shredded when it became soft.

Pleurotus ostreatus commercial spawn was used as the inoculum, collected from a local vendor, and stored in a fridge, and consumed within a month. 1-2 % lime was added to maintain pH, and wheat flour was added as a nutrient by 5% of the dry weight of the substrate. Rigid molds of block and panel were prepared from acrylic molds, 2 mm thick,

size 100 mm x 100 mm x 200 mm, and 300 mm x 300 mm x 25 mm thick, respectively. Circular molds were prepared from a 110 mm-diameter PVC pipe for a 50 mm-thick layer, as shown in Figure 1. Equipment used included an autoclave for sterilization, an incubator to control growth parameters such as temperature and humidity, and an oven for drying, as shown in Figure 2.

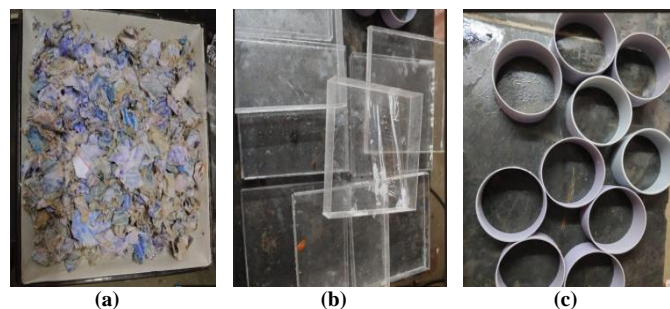


Fig. 1 (a) Paper pulp, (b) Acrylic mold, and (c) PVC circular mold.



Fig. 2 The equipment used for the experiment

3.2. Experimental Design for Process–Property Relationships

This study was designed to develop process–property interrelationships, four key controllable process factors which were monitored and maintained systematically, with other conditions held constant. The experimentation factors were,

- A: Substrate moisture content (spawn, wt.% of dry weight of substrate): 50%, 60%, 70%
- B: Spawn loading (spawn, wt.% of dry weight of substrate): 5%, 10%, 15%
- C: Incubation temperature range: i) 20°C - 25 °C, ii) 25°C - 28°C and iii) 28°C - 32°C
- D: Growth duration: up to 20 days, 25 days, and beyond 30 days.

The fixed process controls used in the study were the paper pulp preparation method, fiber size distribution, sterilization procedure, relative humidity, and drying process. Table 1 results show fixed and variable process components for each experimental condition. Five replicate specimens were prepared, and results are reported as mean \pm standard deviation.

Table 1. Results show s fixed and variable process component

Parameter	Value/Range	Fixed/Variable
Substrate	post-consumer office paper pulp	fixed
Soaking time	24 hours	fixed
Lime addition	2 % by dry weight of substrate.	fixed
Wheat flour substitute	5 % by dry weight of substrate.	fixed
Sterilization	100 °C, 2-3 h	fixed
Initial Moisture	50, 60, and 70%	variable
Spawn loading	5, 10, 15% by dry weight of substrate.	variable
Temperature °C	20-25, 25-28, 28-32	variable
Growth duration	20, 25, 30+ days	variable

3.3. Material Preparation

For material preparation, waste paper was collected and cleaned to remove dust, pins, and plastic fragments, if any. Then the required quantity of material is soaked in potable water for 24 hours. After soaking, the paper was manually shredded, and excess moisture was removed by simple hand pressing, and then the required moisture level was adjusted. Soaking facilitates proper moisture absorption necessary for the subsequent growth of the mycelial composite in the mold [16].

Hydrated lime was added at 2% to the substrate dry weight to adjust pH, and wheat flour was added at 5% of the dry weight of the substrate as a nutrient supplement [17, 18]. To remove earlier contamination of molds, bacteria, or viruses, the prepared material was sterilized in an autoclave at 100°C for 2 to 3 hours. [5] The material is then allowed to cool at room temperature, and after cooling, the spawns are added at inoculum loading of 5%, 10%, or 15% of the substrate's dry weight, distributed layer-wise to promote uniform growth. [12]

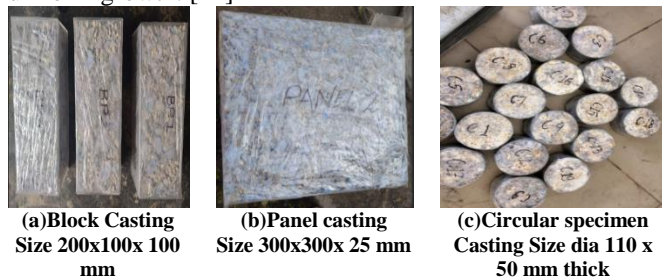


Fig. 3 Shows casting mold a. Block, b. Panel and c. Circular specimen

The inoculated mixture is filled into the molds and packed airtight with transparent plastic paper to observe the formation of MBC, as shown in Figure 3. One or two small pinholes are made to release excess gas. The samples are then incubated in an incubator at the set temperature and a relative humidity greater than 60% in the dark condition. For quality control during incubation, each sample was visually monitored for uniform surface whitening; if any sample was contaminated, it was discarded. After the targeted days, the samples are air-dried for one day, then oven-dried at 50-70°C for two to three days to deactivate fungal growth and reduce moisture. [12]

3.4. Statistical Analysis

Observed results were summarized to their mean values and standard deviations. According to observation, statistics are descriptive and are used to compare different fabrication conditions. This study is a process-property exploration, so it is focused on mycelium growth, specimen density, and after deactivation of mycelium growth, specimens were tested for shrinkage percentage, compressive strength, and thermal conductivity.

3.4.1. Growth Assessment and Quality Control

To ensure actual growth performance in the material, each paper pulp–Pleurotus ostreatus block was first evaluated for visual appearance, growth, quality, and process integrity. After the incubation period, all sample faces were photographed under constant light to assess the full extent of mycelial growth across the entire mold. Attention is provided to uniform surface whitening; if it is absent anywhere, it denotes improper growth of mycelium, which affects the binding of the material, further affecting density and strength. Also, specimens were screened for other contaminants, including discoloration, odor, visible microbial colonies, and bacterial growth. If any such case is found, blocks were discarded from subsequent experimentation, and the frequency of contamination was recorded. Sometimes a sample of a material that cannot hold water, like sawdust, becomes dry; it is wetted again by spraying water and repacked.

3.4.2. Physical Characterization

Physical characterization focused on measuring structural dimensions and weight that are then related to processing and performance. Three-dimensional geometric measurements are recorded for surface irregularity, and specimen volume was evaluated from the averaged dimensions. Bulk density was then calculated from wet and dry mass and average geometric volume, and used to link to process variables such as moisture content and spawn percentage. Dimensional stability was evaluated by measuring shrinkage between the pre and post-growth dimensions before and after deactivation. The evaluated density is then related to porosity, which in turn is linked to strength and thermal performance.[12]

$$\text{Density} = \text{Mass (kg)} / \text{Volume (m}^3\text{)} \quad (1)$$

$$\text{Shrinkage percentage (\%)} = \frac{[(V_1 - V_2)]}{V_1} \times 100, \quad (2)$$

Where V_1 = the wet volume after unmolding of the sample and V_2 = the dry volume after deactivation of the sample.

3.4.3. Mechanical Characterization

The mechanical performance of the blocks was evaluated primarily through a compressive test. The compressive test is the most common and best-performing test for non-load-bearing blocks, insulation cores, and modular components. A universal testing machine was used to conduct testing at a test speed of 5mm/min and a controlled strain of 40% in the specimen. This part was conducted in five replicates. Then, the crushing load value was recorded and calculated using the formula (3) [19]

$$\text{Compressive Strength } (\sigma) = L/A, \quad (3)$$

where L is the compressive Load (Newton), and A is the cross-section of the specimen



(a) Compressive testing (b) Thermal conductivity testing
Fig. 4 Testing of the sample for the compressive test and thermal conductivity

3.4.4. Thermal Characterization

Thermal insulation performance was evaluated using the guarded hot plate method IS: 3346-1980 to measure thermal conductivity, with a controlled boundary that protected against heat loss, using glass wool as the insulating material. Specimens were tested using a steady-state heat-flow method; the color, thickness, and density were recorded before and after testing for each sample to interpret changes resulting from heat application. Thermal conductivity results were measured in (W/m·K), a function of thickness, porosity, and heat conduction of the material.

4. Results and Discussion

4.1. Effect of Substrate Moisture Content

In the current study, five sets of experiments were conducted at moisture content levels of 50 %, 60 %, and 70 %. Where moisture content is related to colonization rate of mycelium on substrate, which is the most prime ordered control variable in the process property chain. The growth was monitored every 5 days by visual appearance for around 30 days. At 50% moisture content, the sample appeared dry, with less growth. At 60% moisture content, growth was satisfactory. At 70% moisture content, no growth occurred,

indicating a marshy condition and a sticky surface. Excess moisture also reduces gas transport through pores, leading to local anaerobic conditions and other contamination, resulting in no mycelial growth. Table 2 results show that MBC, as a consistent growth substrate, requires sufficient water to support hyphal growth. [4]. The 60% moisture-content sample was found to have the optimal water content, exhibiting stable growth, uniform surface coverage, and a uniform block. The process–property interpretation related to moisture content does not simply mean “growth,” but growth to achieve meaningful mechanical strength after deactivation of fungal growth

4.2. Effect of Inoculum Loading (B: 5%, 10%, 15%)

In this study, the substrate, incubation time, and incubation parameter were kept constant; only the spawn percentage was varied at 5%, 10%, and 15% of the substrate dry weight, and the samples were visually monitored at 5-day intervals. Table 3 shows the growth pattern after 30 days. At 5% spawn, growth was very slow compared to the other two sets; it was not uniform throughout, and insufficient colonization was observed near the spawn only. Increasing the spawn percentage from 10% to 15% resulted in faster growth during incubation and reduced the risk of contamination. It was also observed to be uniform throughout the mold, both up and down. After 15 days, all samples were inverted, revealing uniform growth across the mold. No significant difference in growth was observed between 10 % and 15 %; both samples exhibited the same growth pattern throughout the incubation period, suggesting a process-property relationship in which the optimal spawn percentage may be 10 %, thereby reducing spawn costs. This study was necessary because the major binding property of MBC was controlled by fungi mycelium, which interlocks to control density, porosity, and compressive strength.

4.3. Effect of Incubation Temperature

Temperature is a key factor in fungal properties, as it influences growth rate and the quality of hyphal growth. An incubator was used to control temperature during this study, with the temperature range set to average ± 2 °C in the range of 20°C - 25 °C, 25°C - 28°C, and 28°C - 32°C for 30 days, as shown in Table 4, with a moisture content of 60%, and a spawn added were 10%. The samples kept at 20–25 °C grew very slowly, and the temperature was too cold for mycelial growth. Next range: 25–28 °C, producing a small quantity of warmth and an ideal temperature for mycelium growth, resulting in faster growth, uniform binding, and reduced other contamination. This range is suitable for room temperature, eliminating the need for an incubator and reducing the energy required.

Furthermore, the temperature range 28–32 °C exhibited higher temperatures, greater evaporative water loss, and reduced substrate water retention capacity, all of which are required for mycelial growth throughout the incubation period.



Fig. 5 the growth pattern by maturity

Table 2. Moisture content and related growth outcome




Growth image			
Moisture level %	50%	60%	70%
Surface Observation	Dry	Moderately wet	Marshy
Mycelium Growth	Less	Uniform	No growth
Expected Growth	The material was not bound, showing a disintegrated block	This condition showed superior performance to other samples in this study	No block formation observed

Table 3. Inoculum-loading and observed growth results


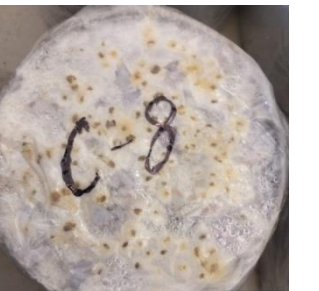




Actual sample			
Spawn%	5%	10%	15%
Observed Growth Pattern	Very little, slow, and non-uniform	Fast growth, uniform throughout the mold	Same as 10%
Expected strength	Lower and variable	Higher and consistent	Similar to 10% pattern
Practical application	Not recommended	Most Suitable	Costly

Table 4. Temperature results and outcomes

Growth specimen			
Temperature °C	20–25 °C	25–28 °C	28–32 °C
Growth Kinetics	Slow growth	Ideal growth	Very slow
Outcome	Needed a longer time for the spreading of mycelium	Faster growth and uniform spreading	No growth observed.

This temperature range exhibited a dry-surface appearance and no growth, indicating process failure. As growth is a significant process parameter, the temperature range for proper mycelial growth is 25–28 °C.

4.4. Effect of Growth duration on Mycelium Growth

The above-mentioned optimal process parameters were maintained, and the growth duration and mycelial network pattern were monitored. On the 20th day, the top surface showed full growth, while the bottom surface showed scarcely any. Subsequently, the samples were inverted to maintain gas transfer throughout. On the 25th day, the entire mold turned white as mycelium spread. Further, by the 30th day, the fruiting body began to protrude. So, ideally, after the 25th day, the sample should be monitored daily, and mycelial deactivation should be carried out, as the fruiting body decomposes more substrate, which will directly affect the strength of the MBC block. The longer the 30 days, the more likely it is to develop a fruiting body, and the higher the processing cost. This mycelial growth is shown in Figure 5.

4.5. Effect on Density and Shrinkage Percentage of MBC Blocks

In this study, density, shrinkage percentage, compressive strength, and thermal conductivity were used to select the optimum process conditions from the above results. 60% moisture, 10% spawn, 25–28 °C, 30 days. For the density and shrinkage study, circular specimens with a diameter of 110 mm and a thickness of 50 mm were used, and specimen masses (C1–C20) were studied. The probable density of the paper-pulp and *P. ostreatus* blocks showed a slight, monotonous decline over the incubation period. The mean density decreased from $906.9 \pm 110.3 \text{ kg m}^{-3}$ (Day 0) to $867.7 \pm 104.4 \text{ kg m}^{-3}$ (Day 30), showing an average mass reduction of $4.31 \pm 0.42\%$ throughout all samples. This slight decline in density, as shown in Figure 6, was in the optimal regime of process parameters and does not show a significant decline during growth. The decrease in density is due to slight substrate decomposition during mycelium growth,

without affecting strength. A greater reduction in density indicates greater substrate degradation, which affects the strength property. The MBC showing higher density is associated with higher compressive strength but lower porosity, which will affect the material's thermal and acoustic properties.

Table 5. Wet density results

Age	Mean density (kg/m ³)	SD (kg/m ³)	Min–Max (kg/m ³)
Day 0	906.9	110.3	770.3–1123.8
Day 5	904.5	109.7	766.0–1119.6
Day 10	893.3	108.2	759.7–1107.0
Day 15	888	107.3	755.5–1100.7
Day 20	881.4	106.4	749.2–1092.3
Day 25	874.4	105.2	745.0–1083.8
Day 30	867.7	104.4	738.7–1075.4

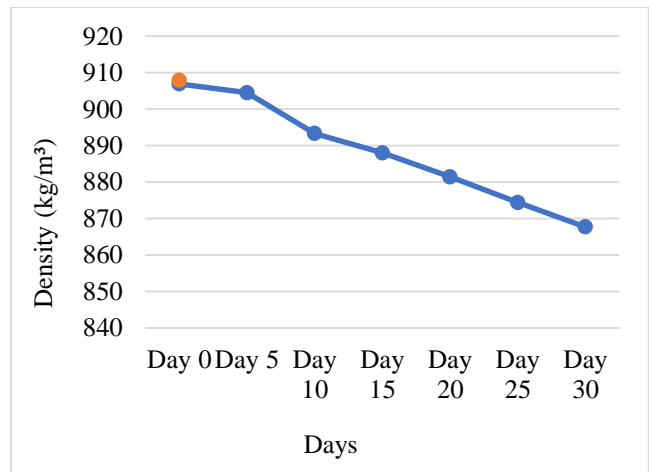


Fig. 6 shows the mean density results (kg/m³)

4.6. Shrinkage and Dimensional Stability

Shrinkage in paper-pulp is a function of initial internal water content, uniformity of the mycelial network, substrate swelling due to moisture required for fungal growth, and drying rate. During development, the hyphal network absorbs moisture and nutrients, forming a binding substrate. The principal constituent of mycelium is water, which, after deactivation, forms a foamy mycelium that forms a chitin-like structure, forming white skin that grows in voids and on the surface of MBC and locks the particles together after shrinking. The paper pulp MBC sample shows an average shrinkage of 19%, as shown in Table 6. A study of shrinkage is essential for understanding the dimensional stability of the composite when used as a building material.

Table 6 shows shrinkage results

Material	Original Dimension (mm)	Dimension After Drying (mm)	Shrinkage %	Avg Shrinkage %
Block	200 × 100 × 100	188 × 92 × 94	18.7	19%
Panel	300 x 300 x 25	287 x 289 x 22	18.9	
Circular mold	Ø110, 50 thick	Ø103, 42 thick	19.3	

4.7. Compressive Test

In the characterization of compressive test, Table 6, below summarizes the average compression response of 20 sets of block and circular specimen paper-pulp and *P. Ostreatus* mycelium block. As shown, brick carried a higher average absolute load (43 kN) because its loaded cross-sectional area was also significant, resulting in a calculated compressive stress of 2.39 N/mm² (2.39 MPa). The cylindrical mold carried an average ultimate load of 20.82 kN and an average compressive strength of 2.56 N/mm² (2.56 MPa) under test conditions as shown in Table 7.

Table 7. Compressive strength results

Material	Load (KN)	Area (mm ²)	Compression strength (N/ mm ²)
Brick	43.0	17971.2	2.39
Circular specimen	20.8	8133.4	2.56

In perspective, the compressive result in optimal conditions likely produced a stronger internal network. Structurally, these strong, effective hyphal bridges between pulp fibers improve interlocking and stress transfer, and delay pore-wall collapse, thereby directly increasing the compressive strength of the specimen. This strength property of MBCs makes them useful for various applications, including packaging, non-load-carrying walls, and insulation panels.

4.8. Thermal Conductance

For the thermal conductivity (λ) of paper-pulp and *P. ostreatus* Mycelium Composite (MBC), the guarded hot plate method was used to test the samples of Ø110 mm × 50 mm circular specimens, yielding a thermal conductivity (λ) of 0.07 W/m·K, as shown in Table 8, which is compared with other insulating materials. In the present study, paper-pulp MBC behaves as a moderate insulator, with a higher density than straw-based materials, which are lightweight and porous, such as wheat straw, soybean straw, and rice straw, and much better than dense mineral/structural materials like sawdust.

Table 8. Thermal conductivity results

Material	Thermal conductivity λ (W/m·K)	Remark
Paper pulp <i>P. ostreatus</i> MBC	0.07	The Experiment specimen
Mycelium composite (low-density best case)	0.036	[20]
Cellulose fiber insulation	0.043	[21]
Glass wool	0.038	[22]
Rock wool	0.044	[22]
EPS (expanded polystyrene)	0.03	[22]
XPS (extruded polystyrene)	0.03	[23]
PU foam (rigid)	0.025	[24]

Compared to other insulation materials, Paper pulp MBC had a thermal conductivity of 0.07 W/m·K, which is higher than those of other researched mycelium composites and commercial insulators.

Mycelium composites developed from agricultural waste, with high porosity and low density, reported λ of 0.03–0.04 W/m·K, which is comparable to the ranges for conventional EPS and glass wool (0.03–0.04 W/m·K) [20]. Researcher Aravena, in his study, used wheat straw and *P. ostreatus* blocks and reported an average thermal conductivity λ of 0.032 ± 0.001 W/m·K, which was considered a high thermal insulator at low density, indicating that it is the best-case insulating material. [25]

From the point of view of the process–property relationship, the higher λ of the paper-pulp MBC (0.07 W/m·K) is a property of microstructure that are denser which is result of “optimum growth” conditions expecting better integrity and compressive strength, but made the material less porous than other MBCs which are delivering the lowest λ (0.03–0.04 W/m·K) and better thermal performance.

4.9. Comparative Discussion with Published Mycelium Composite Studies

The present paper-pulp composite exhibits a different process-property balance from many other low-density mycelium composites reported in earlier literature. The process-property relationship observed in this study, conditions that produced stable and uniform fungal colonization conditions, especially 60% substrate moisture, 10% spawn loading, incubation at 25-28 °C, and approximately 30 days of growth. Under optimum process range, the developed composite showed relatively high density with compressive strengths of 2.39 MPa for blocks and 2.56 MPa for circular specimens, while the thermal conductivity was observed as 0.07 W/m·K. This indicates that the paper pulp composite does not behave as a light insulation foam; instead, it exhibits a denser mycelium composite with moderate insulating capacity and improved integrity compared with straw-based or highly porous mycelium composites reported in prior studies.

When compared with the literature summarized in Appendix A, the compressive strength performance of the present study is higher than many other agro-industrial waste mycelium composites reported with strengths lower than 1.5 MPa, developed with composite materials from sawdust, bagasse, coffee-husk, straw systems, hemp-shive, and beechwood. However, at the same time, in the broader literature, the present results exceed the highest strengths, since some composites, such as spent coffee-ground composites and dense-board composites, have higher compressive strength, approximately 1.65-2.92 MPa and 0.71-4.44 MPa, respectively. Therefore, the present paper-pulp study is reported in the middle position.

Lower-density mycelium composite developed from agricultural waste showed lesser thermal conductivity values in the range of about 0.03-0.04 W/m·K [26, 27], due to their higher porosity structure, which reduces solid-phase heat conduction. However, highly porous material often exhibits lower density and lower compressive strength. In contrast, the paper-pulp mycelium composite appears to have a more compact and denser internal network, which improves internal bonding and transfers stress, increasing heat conduction through the denser microstructure. Looking at thermal conductivity, the measured conductivity of 0.07 W/m·K is higher than the mycelium composites reported in the literature, which falls in the range between 0.029–0.058 W/m·K, particularly for lightweight straw-based composites. Since the greater density, strong bonding, and higher compressive strength show less porosity and higher heat conductance, even though thermal value is in a moderate range and can be considered as a moderate bio-based insulating material suited for semi-rigid non-structural.

Direct comparison of previous studies will be deferred, since all parameters, such as substrate type, fungal species,

spawn source, specimen shape, initial moisture state during incubation, etc., and analysis methods may vary throughout all the literature. The present study shows that recycled paper pulp can be recycled into a mycelium composite with a reproducible process window for non-structural building material.

5. Sustainability Implications, Limitations, and Practical Relevance

The paper pulp mycelium composite has sustainability potential because it uses recycled paper pulp as a basic raw material and fungal mycelium as a biological binding network, as opposed to environmentally harmful synthetic binders. Even these MBCs may offer environmentally friendly advantages over non-biodegradable petrochemical-based foams and mineral insulation products, which should not be overstated without proper formal quantification.

Even though fabrication consumes energy for sterilization, controlled incubation, and oven drying, this material can be described as a bio-based and waste-derived sustainable material that requires cradle-to-grave life-cycle assessment to analyze biodegradability, durability, and service-life performance. The study also has several technical limitations. First, additional performance indicators such as water absorption, fire resistance, biodegradation, and durability were not fully quantified in the present experimentation. Second, alternative-fungus control needs to be included along with full predictive modeling. These limitations do not disqualify the reported trends, but they define the boundaries of the current study.

From a commercial perspective, the results suggest that paper-pulp/*Pleurotus ostreatus* composites may be suited for non-structural, lightweight building material, such as interior partition core, packaging, or insulating board with desired shapes.

6. Conclusion

A Process property relationship in the mycelium composite block of paper pulp and *Pleurotus ostreatus* is developed by stepwise linking growth parameters to output performance within a controlled growth range. In this study optimum growth parameter derived are; 60% initial moisture in substrate, 10% spawn by dry weight of substrate, 25–28 °C incubation temperature, and around 30 days growth period to enhance uniform mycelium throughout mycelium specimen, to avoid failure behavior like incomplete binding due to low moisture or marshy condition due to high humidity, low spawn % slow growth, low and high temperature then room temperature not suitable for mycelium growth and growth period extended beyond 30 days the fruiting body degrade substrate more affecting strength of the MBC.

In the optimum process range, density variation also remained controlled: the mean wet density readings observed were from $906.9 \pm 110.3 \text{ kg m}^{-3}$ to $867.7 \pm 104.4 \text{ kg m}^{-3}$ over an incubation period of 30 days, implying that the growth of mycelium was gradual, structural binding and network formation rather than fast substrate degradation, which eventually affects mechanical strength. Dimensional stability showed shrinkage of around 19% for the block and panel after drying, and 18.8% for the circular specimens after drying, due to the removal of the initial water added to the substrate for mycelium growth and the subsequent dehydration of the hyphal skeleton. It is not a drawback, but the process of tightening the pore network improves binding and load transfer. Density and pore tightening cumulatively enhanced the compressive strength of the block to 2.39 MPa and of cylindrical specimens to 2.56 MPa, indicates moderate strength for nonstructural applications.

However, thermal conductivity was negatively affected, yielding $\lambda = 0.07 \text{ W/m}\cdot\text{K}$ via guarded hot-plate testing, due to a high-density, continuous network that elevated conductance. Generally, a lower MBC density yields high-performance foams; the observed conductivity is higher but falls within a functional insulation band for bio-based boards, where strength, handling, and durability are prioritized. Overall, this paper guides the development of process-property relationships using paper pulp and *Pleurotus ostreatus*.

According to the present experimental contribution, this material does not outperform all reported MBCs, but it establishes a relevant, reproducible process window and an analysis of the practical process-property relationship to

develop recycled paper pulp and *Pleurotus ostreatus* composites for non-structural building materials.

6.1. Future Work

This study had a significant focus on improving strength and insulation, but increasing strength is needed to improve density, which eventually drops in thermal conductivity (λ) results. To improve porosity, this substrate can be combined with a straw-based material, making the material construction-ready for thermal and acoustic performance. Additionally, the study can incorporate coatings to reduce moisture and enhance fire resistance, thereby enhancing durability and strength. For the same strength, durability, and humidity resistance, MBCs can be laminated with various sheet materials.

Further, broader statistical and predictive modeling should be developed for a larger database to identify the interaction between processing variables and properties. Finally, formal life-cycle assessment could clearly explain the environmental advantages of paper-pulp mycelium composites compared with conventional and other bio-based materials.

Conflicts of Interest

No conflict of interest regarding the publication of this paper.

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Appendix A

Table 9. Summary of processing parameters, mechanical and thermal properties, and applications of mycelium-based composites

Substrate	Species	Spawn Loading (w/w of dry substrate)	Initial Moisture Content	Substrate Sterilization	Growth Time (days)	Compressive Strength (MPa)	Thermal Conductivity (W/m·K)	Application	Reference
Sawdust + bamboo fibers (0–40%)	<i>Trametes versicolor</i>	10%	60-70%	Autoclave (121°C, 20 min)	25-30	0.06- 0.19	NR	Construction (optimized composites)	[28]
Sawdust, corn husk, rice straw	<i>Ganoderma fornicatum</i> , <i>G. williamsianum</i> , <i>Lentinus sajor-caju</i> , <i>Schizophyllum commune</i>	1%	60%	Autoclave (121°C, 60 min)	21-28	0.25-1.87	0.074 - 0.087	Thermal/acoustic insulation, packaging	[24]
Sawdust, bagasse, coffee husk	<i>Pleurotus ostreatus</i>	10%	60-70%	Autoclave (121°C, 60 min)	21-27	0.25-0.75	NR	Mycoblock (construction)	[29]
Sawdust, straw (various ratios)	<i>Pleurotus ostreatus</i>	7%	65-70%	Autoclave (121°C, 40 min)	35-49	0.07-0.50	NR	Compressive structures	[30]
Sawdust + empty fruit bunch (EFB)	<i>Ganoderma lucidum</i>	1%	60%	Autoclave (120°C, 60 min)	21–30	0.71-4.44	NR	Dense boards (weathering study)	[31]
Hemp shives, beechwood sawdust	<i>Ganoderma resinaceum</i> , <i>Trametes versicolor</i>	10%	60-80%	Autoclave (121°C, 20 min)	14-40	0.48-1.32	0.04-0.06	Formwork, insulation, particleboard	[32]
Arboloco pith + Kikuyu grass	<i>Ganoderma lucidum</i>	5% (wet basis)	94%	Autoclave (121°C, 2 h, Tyndall method)	20	0.017-0.169 (at 10-50% deformation)	0.045-0.047	Lightweight insulation panels	[33]

Hemp hurds + wheat bran	Ganoderma lucidum	1%	60%	Autoclave (121°C, 60 min)	21-30	1.2 ± 0.12 compressed	NR	Reinforced composites	[34]
Hemp shives	Fomes fomentarius	10%	60-80%	Autoclave (121°C, 20 min)	14-21	0.02-0.05 (at 10% strain)	0.041-0.046	Thermal insulation, particleboard	[35]
Spent coffee grounds + pineapple fiber (10–30%)	Pleurotus ostreatus	1%	70-80%	Autoclave (121°C, 30 min)	28	1.65-2.92	NR	Packaging, light construction, sound absorption	[36]
Beechwood sawdust + hemp hurds	Ganoderma resinaceum	10%	60-80%	Autoclave (121°C, 20 min)	28	1.29-1.32	0.044-0.058	Insulation, formwork	[37]
Wheat straws + polypropylene with bacterial spores	Ganoderma lucidum	NR	NR	Autoclave (121°C, 20 min)	30-35	0.07 (at 25% deformation)	0.029-0.035	Thermal insulation (board)	[38]
Hemp hurds + laterite particles	Pleurotus ostreatus	NR	NR	Autoclave (121°C, 90 min)	NR	0.9 (at 10% deformation)	NR	Structural biocomposites	[6]
Mycocrete paste (beechwood sawdust + paper additives) + knitted textile formwork	Ganoderma lucidum	2%	NR	Autoclave (121°C, 30 min)	8 (in mold) + 8 (post-mold)	0.97 ± 0.10	NR	Large-scale architectural components (BioKnit)	[39]
Albizia sawdust sawdust	Lentinus squarrosulus	10%	60-70%	Autoclave (121°C, 20 min)	10	0.13	NR	Packaging, insulation	[40]
Straw fibres	Pleurotus ostreatus	75% (primary spawn of total volume)	NR	Autoclave (126°C, 1 h)	20	NR	0.122	Building insulation panels	[41]

NR: Not Reported