



# MycoMax

Reinforced load-bearing MBC

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**Reinforced load-bearing MBC**

**MSc Graduation Thesis Report**

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# Abstract

This thesis presents a method of reinforcing Mycelium-Based Composites (MBCs) using woven bamboo fibres to improve compressive strength for potential load-bearing applications. While MBCs offer advantages such as biodegradability, low embodied energy and the use of agricultural waste streams, their limited structural capacity currently restricts their application in structural systems.

The research investigates how reinforcement geometry, scaffold porosity, substrate density and unit cell size influence the growth behaviour and mechanical performance of MBCs. Inspired by traditional weaving techniques, woven bamboo mats were developed as reinforcement scaffolds using variations in strip width, thickness and grid spacing to control porosity and density. Bamboo was selected due to its high stiffness, accessibility and compatibility with mycelial growth, while hemp was identified as the most suitable secondary substrate for improved binding and density.

The material system was further developed into a constant 50 mm thick section incorporating two layers of woven bamboo mat reinforcement. Compression testing validated the contribution of bamboo reinforcement, where the large width strip (10mm) of woven bamboo specimen achieved a compressive strength of 1.157 MPa compared to 0.692 MPa for the specimen without bamboo reinforcement. Comparisons between large-width (10 mm) and small-width (5 mm) woven mats also demonstrated the importance of scaffold cell size, with the smaller grid achieving 0.717 MPa and complete delamination. Similar behaviour was observed during Stage 2A, where the larger grid configuration showed improved survival during contamination and better mycelial growth.

Further comparisons between bamboo origin types demonstrated the importance of fibre texture and surface characteristics for mycelial binding. Overall, the research demonstrates a framework for material-driven and performance-based design in engineered MBC systems reinforced with woven bamboo fibres, contributing toward the development of load-bearing bio-based construction materials.

Keyword: Mycelium-based composites, bamboo reinforcement, scaffold design, bio-based materials.



# Acknowledgements

*“The future of materials is grown, not manufactured.”*

*- Eben Bayer (Ecovative Design)*



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# Acronyms

EPD: Environmental product declaration

GWP: Global warming potential

LCA: Life cycle assessment

MBC: Mycelium bio-composites

WBM: Woven Bamboo Mat

CO2e - Carbon Dioxide equivalent

EoL - End-of-Life

SEM - Scanning Electron Microscopy

VOCs - Volatile Organic Compounds



MycMax: Reinforced load-bearing MBC

# Glossary

**Autoclaving:** super-powered sterilizing; It's a process where you use high-pressure steam, usually at around 121°C, to kill off any bacteria, molds, or spores in a material.

**Bran:** It adds extra nutrients (especially protein and carbs) that mycelium loves. This helps it grow faster and build a stronger network

**Brown rot fungus:** A fungus type that feeds on cellulose

**Bamboo culms:** the main above-ground, aerial stem or stalk of the bamboo plant

**Culture:** Vegetative part of fungus; is a nutrient-rich solution used to grow and expand mushroom mycelium before transferring it to a growing medium

**ELMS:** Engineered living materials (fungal based)

**Field Capacity (of the fibre):** Refers to the ideal moisture content in the substrate (fibre), allowing oxygen to reach mycelium while providing enough moisture for growth

**Hybrids:** Fungal scaffolds

**Hydrophobins:** active protein coatings; fungi secrete proteins like lipid

**Hyphae:** Body of the fungus

**Inoculation:** cultivation process; the action of immunizing someone/something against a disease by introducing infective material, microorganisms, or vaccine into the body.

**MBC:** Mycelium Bio Composite / Mycelium based composite

**Spores:** Seed of the fungus

**Substrate:** a loose network of hyphae which grows by extensive branching on the surface of the substrate

**Taxonomy:** A classification system

**White rot fungus:** A fungus type that feeds on lignin

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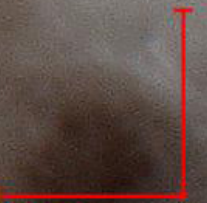
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# LITERATURE REVIEW

Part A



# 1.0

## Research framework

### 1.1 Introduction

Our current building construction industry heavily relies on fossil fuel derived energy and material production. The current construction industry depends heavily on fossil-fuel based energy and materials. This dependence is environmentally unsustainable and reduces long-term resource security. To move towards a more sustainable system of production, use and reuse, alternative materials and fabrication methods need to be explored. Materials previously considered waste, weak or low-value may offer new opportunities to overcome the limitations of conventional

construction practices (Heisel, 2017).

Bio-based construction materials such as bamboo, timber, hemp, straw, cork, mycelium and bioplastics offer significantly lower carbon footprints and can contribute to carbon storage. This makes them more sustainable alternatives (Aidung et al., 2022; Armstrong, 2023). The proposed solutions show strong potential for long-term viability in terms of material abundance, thus aiming for longevity.

Bio-based alternatives and living materials such as mycelium-bio composites (MBCs) are attracting attention for the built environment. This is due to their low embodied energy, biodegradability and potential to reduce the carbon footprint of walls and blocks significantly (Alaneme et al., 2023).

Mycelium is a very **compelling binding compound** that stabilizes fibres obtained from agricultural waste. In line with the principles of the circular economy, these materials can be used to manufacture new building components that are suitable for practical applications. This contributes to improving the environmental and economic sustainability of the construction industry (Almpani-Lekka et al., 2021). Several studies and prototype developments

have also been conducted to evaluate the structural performance and durability of mycelium-based materials under exposed environmental conditions.

Mycelium-bio composites (MBCs) are a category of engineered living materials (ELMs) produced by cultivating fungi on lignocellulosic substrates. These sustainable bio-composites utilise fungal mycelium as a natural binder to bond organic feedstocks, such as agricultural waste. MBCs are **biodegradable, lightweight, and highly customisable**. For long-term applications, the composites can be dried to stop the fungus from growing. This results in materials with functional properties including effective acoustic insulation, hydrophobicity, thermal insulation, and fire resistance (Sharma & Le Ferrand, 2025).

The use of MBCs as insulation takes advantage of the material's inherent thermal and fire-resistant properties. Biohm's mycelium insulation panels achieve a thermal conductivity of **0.024 W/mK**, outperforming several widely used insulation materials, including glass fibre (0.032–0.044 W/mK), mineral wool (0.032–0.044 W/mK), expanded polystyrene (0.036 W/mK), and extruded polystyrene (0.029–0.036 W/mK) (Bitting et al., 2022). In addition, the relatively low manufacturing cost of mycelium insulation enables it to remain competitive with conventional materials. With regards to acoustic properties, they vary between products, several companies

and designers have explored the use of mycelium materials in acoustic panelling systems. Pelletier et al., in "An Evaluation Study of Pressure-Compressed Acoustic Absorbers Grown on Agricultural By-Products", reported that an acoustic ceiling tile with a density of 0.71 g/cm<sup>3</sup> and an MBC tile with a **density of 0.42 g/cm<sup>3</sup>** achieved sound attenuation values of 7.6 and 7.1, respectively. These results indicate that MBC panels can serve as a competitive alternative to conventional acoustic tiles (Bitting et al., 2022).

When compared to conventional construction materials (Table. 01), mycelium-based composites offer several advantages, including lower production costs, better recyclability, easier raw material sourcing and low energy manufacturing processes. In comparison, materials such as polymers, gypsum and cement require more energy-intensive manufacturing.

Leading companies in the mycelium industry have demonstrated the application potential of mycelium-based composites through commercially developed products. Myceen and Mogu have produced insulation and acoustic panels with properties related to thermal conductivity of 0.037 W/mK, fire resistance, and acoustic performance. Mogu acoustic panels have achieved a Class B-s1-d0 fire rating with an exclusive eco-friendly fire retardant finishing for interior applications.

Table 01: Material Experimentation: Methodology (Source: Alemu et al. (2022))

Material Property	Mycelium-based Materials	Polymer Materials	Gypsum-based Materials	Cement Material
Density (kg/m <sup>3</sup> )	110 ± 0.01 to 330 ± 0.05	22 to 30	417–945	1800–1950
Cost (\$/kg)	0.07–0.17	2.1–2.3	1.4–11	-
Cost (\$/m <sup>3</sup> )	19.05	-	-	942.86
Compressive strength (kPa)	360 ± 5 to 520 ± 8	69–400	60–550	3450
Water absorption (%)	200	6.9	52	12
Recyclability	Fully degradable	Decades, century	Years, decades	None
Raw materials	Mycelium and organic wastes or substrates	Polymers and natural gases	Adhesives, sawdust, and chips	Cement and sand
Manufacturing process	Moulding and growing	Polymerisation and expansion	Lathing, pressing, resin infusion, and milling	Mixing, moulding, and curing



Figure 01: (left) Myceen Insulation Panels; (right) Mogu Acoustic Panels (Source: Myceen; Mogu)

In addition, Ecovative has developed mycelium-based façade panels using hemp substrates for affordable housing project Phoenix in California. They also claim for the panels to be load-bearing, unfortunately no proper information confirms that. These examples show that mycelium composites are being developed into practical construction materials with increasing market applicability.

However, despite their environmental advantages, these materials face several challenges, including inconsistent quality, sensitivity to moisture, fire hazards, and limited durability, which restrict their large-scale adoption in the construction industry (Attias et al., 2020; Aiduang et al., 2022). This significantly reduces the likelihood of competing with established, durable market-standard materials and limits the potential for early replacement. Substantial development of the **material's mechanical properties** is therefore required for it to

meet prevailing industry standards.

## 1.2 State of the art review

As per Bitting et al. (2022) MBCs and pure mycelium materials (PMMs) (see Fig. 02) exhibit mechanical properties comparable to conventional synthetic materials such as elastomers, polyurethane, and polystyrene foams. In particular, their Young's modulus values indicate a relatively high degree of elasticity, suggesting that these materials are well-suited for applications requiring resilient performance. However, most MBCs today have been applied in non-structural or insulation roles, because mechanical strength (especially compressive and shear) remains a limiting factor (Javadian et al., 2020). These materials are underexplored when compared to market standards and hold large potential.

Mycelium-based materials exhibit **low compressive strength (0.1–0.2 MPa without**

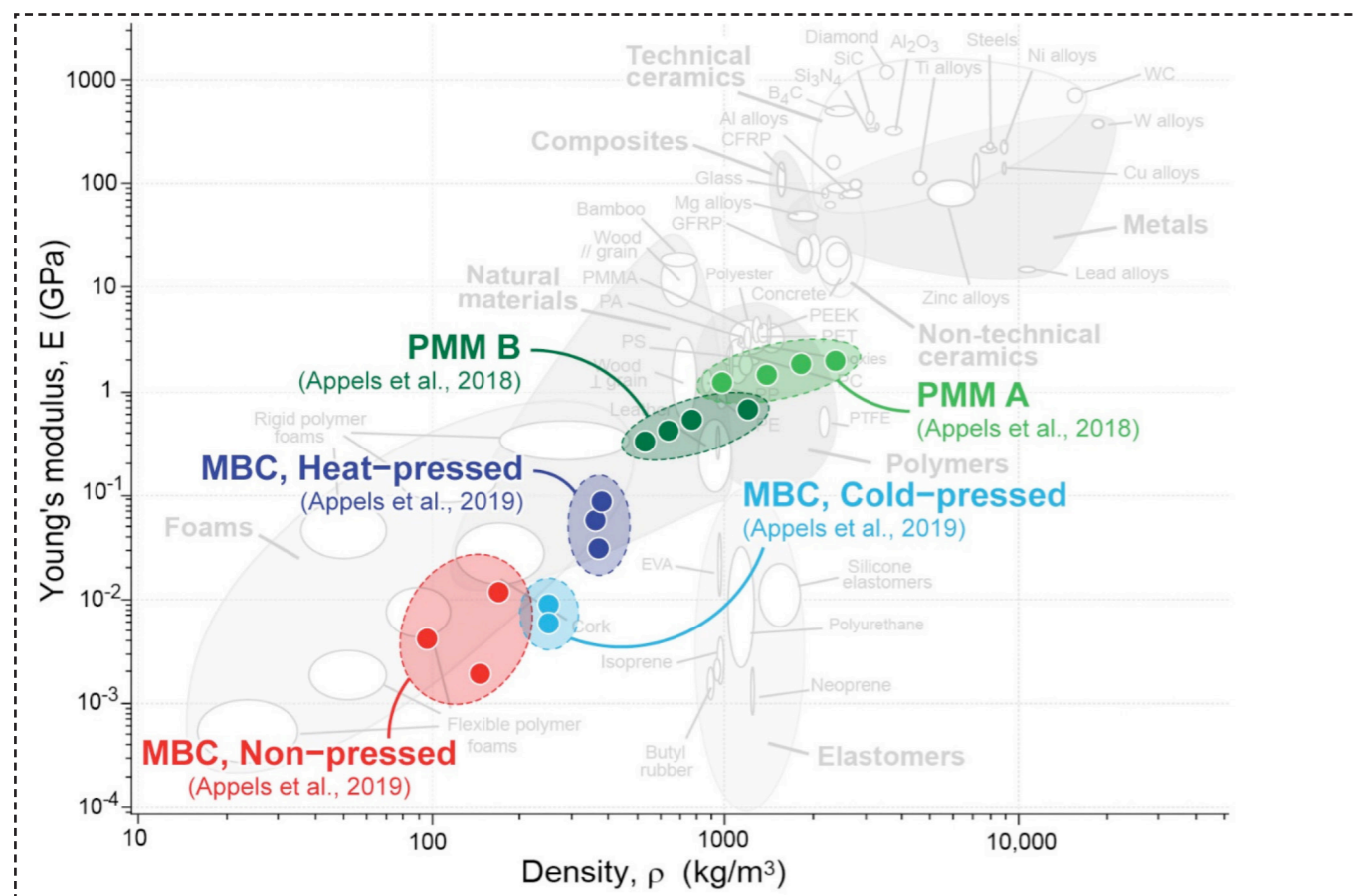


Figure 02: Comparison of MBCs to standard market materials (Source: Bitting et al., 2022)

**compaction**) and the material largely performs better under compression. This limits their structural use largely. Despite this, its lightweight nature provides advantageous strength-to-weight ratios compared to concrete, highlighting the potential of working towards strategies for optimized material distribution for building applications (Voutetaki & Mpalaskas, 2024). Recent advances suggest that with methods like optimized substrates, fungal species, and designed reinforcement the compressive performance of MBCs can be enhanced (Saez et al., 2024). Further development of proof-of-concept studies toward targeted, performance driven solutions may therefore contribute to addressing real-world construction challenges.

## 1.3 Research objective

The development of conventional materials such as metals, steel, and concrete has traditionally focused on increasing allowable stresses to achieve greater structural strength. To enable the structural use of such low-strength materials like MBCs, geometric design becomes critical, allowing loads to be carried primarily through compression (Bitting et al., 2022).

This study investigates the material design of MBCs to enhance their compressive properties. It explores how structural capacity can be optimized through the design of reinforcement geometry and the selection of compatible substrate materials. Emphasis is placed on the bonding quality between the mycelium and the substrate, as it plays a critical role in determining mechanical performance. The research examines how fungal species selection, substrate composition, and the use of functional additives influence mycelial growth, binding efficiency, and mechanical characteristics. In addition, the form and arrangement of the substrate are investigated as key design parameters, as they directly affect porosity and density, which in turn influence mechanical behavior. The choice of substrate material to be compatible to the form then plays a key role in the production

while making sure mycelium's growing quality is not compromised. Bamboo was selected as the primary substrate material. Compared to alternative substrate options, bamboo exhibits higher stiffness and tensile capacity. This enabled the creation of forms through weaving techniques. Furthermore, the weaving pattern can be controlled to achieve a uniform material density, which supports consistent and high-quality mycelium growth.

Lastly, the study considers the importance of assembly methods, and controlled fabrication environments to minimize contamination. Through this integrated approach the research aims to develop compression-optimized MBC building elements suitable for architectural and structural applications.

## 1.4 Research question

This research is about Mycelium being explored as a binder to create better strength-building materials by developing reinforcement strategies. **Exploring different iterations of compression-optimised scaffold forms by using Bamboo weaving techniques as the base reinforcement substrate material.** Thus, posing the research question:

**How can mycelium bio-composites (MBCs) be engineered using woven bamboo fibres as reinforcement to achieve increased compressive mechanical properties for load-bearing applications?**

a) Material composition

- What types of substrates are usually used for the production of MBCs?
- How does the type of substrate material & its composition affect its binding efficiency with mycelium?
- What is the optimal material form & its porosity to achieve the adequate density in turn helping with the structural capacity?

- What porosity characteristics support effective mycelial growth while maintaining standardised material thickness?

- What are the prevailing test results of mechanical (tension & compression) characteristics of MBCs?

b) Reinforcements

- What is the current status quo of MBCs for fabrication and reinforcement strategies that have enabled MBCs to perform in load-bearing structural applications?

- How can reinforcement scaffold geometry improve compressive strength in MBCs?

- What reinforcement forms have proven to be or are a potential to improve compressive strength in MBCs?

c) Bamboo reinforcement

- What is the compatibility of bamboo with mycelium that serves as a stiff reinforcement scaffold material to execute the forms?

- Which weaving patterns in bamboo with the right porosity for mycelium to grow help in designing higher compressive strength reinforcement?

1.5 Methodology

One method for improving the mechanical performance of mycelium-based composites (MBCs) is mechanical pressing; however, this often leads to a **loss of geometric integrity and inherent mechanical properties**. An alternative approach involves increasing the density of the hyphal network to strengthen the binding structure. Achieving a uniformly dense mycelial growth is challenging, as a compact fungal skin typically forms on the surface of the substrate, restricting oxygen and moisture diffusion to the interior and resulting in a low-density internal network.

The **use of porous substrates can enhance**

**oxygen transport**, promoting improved mycelium growth and stiffness while also enhancing functional performance through increased surface area. Although the porosity of loose lignocellulosic substrates can be adjusted by **modifying particle size**, the discontinuous nature of these particles still leads to weak mechanical properties. In contrast, rigid porous lignocellulosic bio-based substrates, provide greater structural stability. **Moreover, designed scaffold systems enable precise control over architecture and porosity, allowing mechanical strength and functional properties to be tailored** (Sharma & Le Ferrand, 2025).

The research follows a 3-part methodology:

Part A) Literature review  
Design and development of optimized compressive load-bearing scaffold geometries using bamboo as the lignocellulosic substrate material. Exploring multiple bamboo weaving techniques in the process.

2) Using validated substrate formulations from previous research incorporating functional additives and secondary lignocellulose substrates for different iterations.

3) Comparative performance analysis of all specimens to identify mechanical characterizations that achieve increased compressive strength without compromising acoustic, thermal, and fire-resistance properties.

Part B) Material experimentation

Part C) Product development and application

1.6 Societal relevance

The adoption of mycelium-based building elements can support a shift towards locally sourced, low-impact building materials, reducing dependence on global petrochemical supply chains. Mycelium can be cultivated using locally available

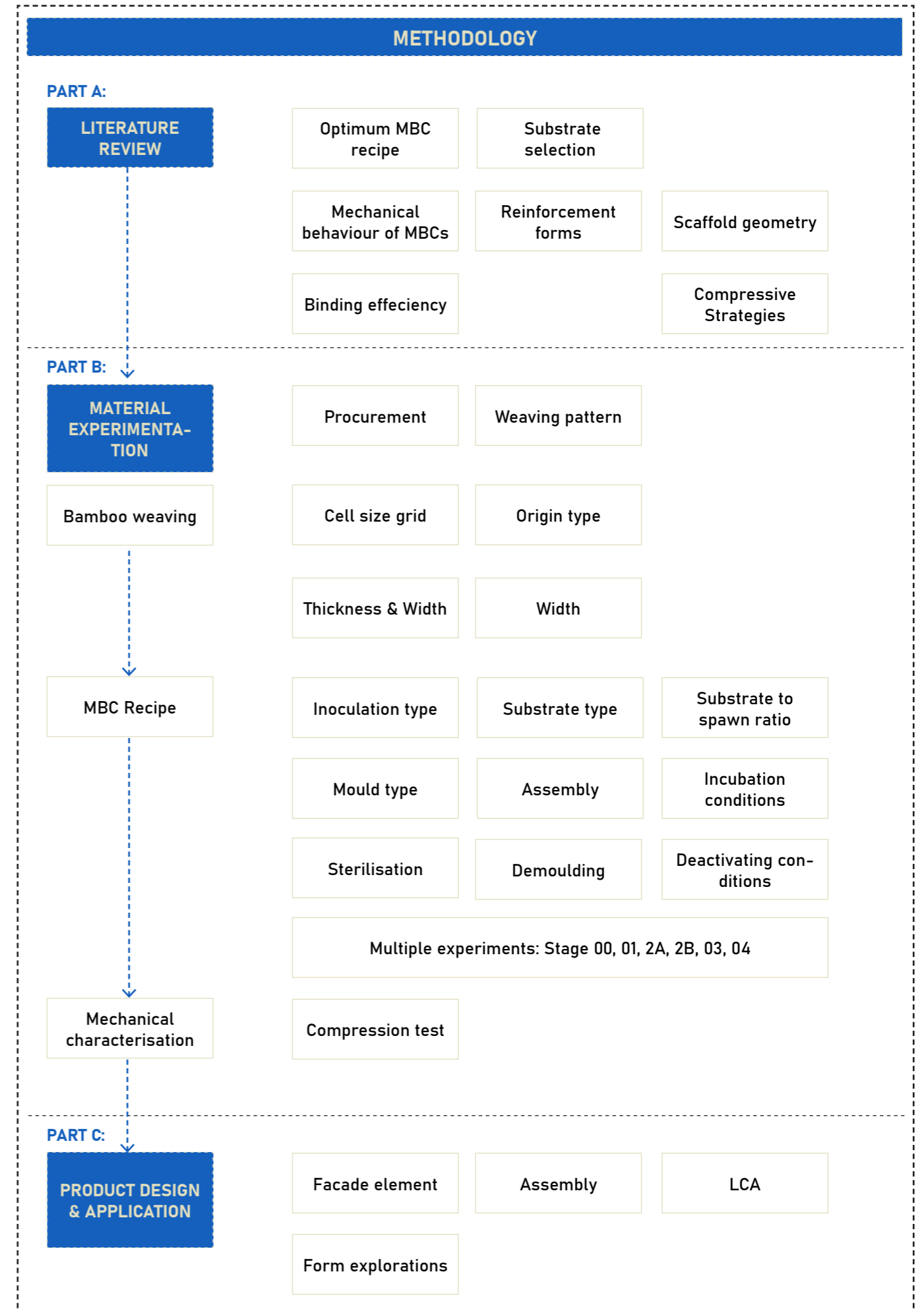


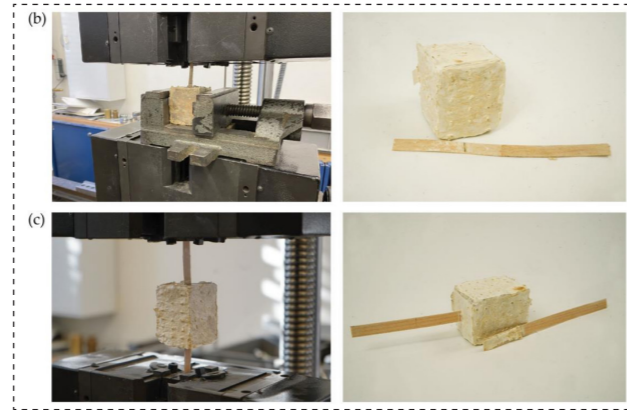
Figure 03: Material Experimentation: Methodology (Author)

agricultural waste, communities may develop **decentralized production systems**. This creates new opportunities for **local employment and material innovation**.

MBCs also help utilise agricultural waste streams that might have otherwise been incinerated therefore creating more carbon. Additionally, MBCs introduce an **alternative material aesthetic**. It promotes organic textures and forms, therefore challenging conventional perceptions of building materials and helps increase the view of architectural expression. MBCs being porous in nature contributes to **improved indoor environmental quality** by passive air filtration. It helps reduce the reliance on synthetic interior finishes that may emit harmful substances such as formaldehyde. Furthermore, the use of MBCs **can reduce pressure on conventional resources** such as timber, which require long periods to replenish and are often imported, incurring higher carbon emissions. From a production perspective, they can be grown and **moulded into complex geometries** with minimal additional processing. More broadly, it promotes a cultural shift toward bio-based construction, where materials are grown rather than extracted.

# 2.0

## Material behaviour of Mycelium in Mycelium-based composites (MBCs)



**Figure 04:** Fig X: Samples during testing and after failure: (b) One-sided veneer pull-out test; (c) Two-sided unwelded veneer pull-out test Note. (Source: E. Özdemir et al., 2022)

### 2.1 Mycelium as a binding matrix

As per early research, mycelium was initially applied in packaging and later in construction as an insulating material. In the past decade, it has expanded into architectural applications, while current studies investigate reinforcement with natural fibers to improve mechanical strength and support self-bearing structural systems. Mycelium's substrate-binding capability and its inherent self-assembling biological properties support its potential for use in eco-friendly construction systems (Voutetaki & Mpalaskas, 2024).

In one of the research studies, pull-out tests were conducted to evaluate the binding strength of mycelium in relation to different connection types in the substrate. The results indicated relatively strong bonding between the mycelium matrix and the veneer reinforcement. Sample (c), which was a single veneer strip (See Fig. X), exhibited a bond strength of 0.34 MPa. Whereas, sample (d), with two overlapped veneer strips, showed a slightly higher bond strength of 0.36 MPa. This increase in the strength in sample (d) can be indicated to enhanced mycelium growth around and between the overlapping veneer layers, resulting in improved interfacial bonding. In contrast, the single-strip configuration provided a smaller surface area for mycelial attachment, leading to comparatively lower

bonding performance. (Özdemir et al., 2022)

#### 2.1.1. Type of mycelium

Different fungal species can significantly influence the density, tensile strength, and compressive strength of MBCs. Consequently, the selection of mycelium strains is dependent on the performance characteristics of the bio-composite. Variations in **hyphal morphology, including filament diameter, cell wall composition, and branching patterns**, directly affect the density and mechanical performance of the mycelial network, as well as its capacity to bind substrates. Fungal species such as *Pleurotus ostreatus* form a dense mycelial layer, commonly referred to as a fungal mycelium skin, at the interface between the substrate and the surrounding air, which enhances the mechanical strength of the composite. Thus, it has been shown to produce mycelial fibres with higher compressive strength than conventional insulation materials, offering improved structural stability and longevity. As per Table 02, wood sawdust results in imparting higher stable strength to the composite with any combination of the fungus type. The compressive strength ranges close to 1850kPa - 1870kPa. Surprisingly, in one of the studies, coffee grounds with 10% pineapple fiber results in a higher compressive strength of 2920 kPa. Although this is lower than conventional concrete or

**Table 02:** Summary of resultant mechanical properties in comparison to mycelium types and substrate types in production of MBCs (Adapted from Voutetaki & Mpalaskas, 2024)

Fiber Substrate	Type of Mycelium	Density (kg/m <sup>3</sup> )	Flexural strength (kPa)	Compression (kPa)	Citation Reference
Wood chips, hemp hurd	Coriolus Versicolor	260	N/A	93	Lelivelt et al., 2015
Wood chips and hemp fiber	Pleurotus ostreatus	130	347	452	Etinosa 2017 Thesis
Wood veneer and hemp hurds	Ganoderma lucidum	145	160	1200	Özdemir et al., 2022
Hemp hurds	Pleurotus Ostreatus	N/A	N/A	700	Etinosa et al., 2023
Hemp	Trametes versicolor	99	N/A	510	Elsacker et al., 2019
Sawdust 90% and wheat 10%	Pleurotus ostreatus	493	N/A	1380	Ghazvinian et al., 2019
Sawdust and wheat bran	Lentinus velutinus	N/A	N/A	1280	Bruscato et al., 2019
Cotton stalk, wheat bran	Pleurotus ostreatus	N/A	N/A	508	Gou et al., 2021
Beech Sawdust	Pleurotus ostreatus	260	110	2490	Vašatko et al., 2022
Straw	Pleurotus ostreatus	132	370	210	Ghazvinian et al., 2022
Rice straw	Lentinus squarrosulus	N/A	N/A	540	Ly et al., 2022
Bamboo	Pleurotus ostreatus spawn	N/A	N/A	500	Soh et al., 2023
Bamboo	Trimitic fungi species	180	450	190	Bagheriehnajjar et al., 2023
Coffee grounds with pineapple fiber	Pleurotus Ostreatus	360	200	2920	Kohphaisansom bat et al., 2023

clay bricks, which usually have compressive strengths between 15,000 and 40,000 kPa, the result is still promising for a lightweight bio-composite material developed from agricultural waste streams. (Voutetaki & Mpalaskas, 2024)

*Pleurotus ostreatus* and *Ganoderma lucidum* are two fungal species commonly used in mycelium-based structural research. Both species are commercially available and widely accessible for experimental applications. *Ganoderma lucidum*, commonly known as yellow reishi, typically grows more slowly but is recognised for developing a denser and stronger mycelial network.

According to Alemu et al., fungal species belonging to the order Agaricales, particularly *Pleurotus ostreatus*, are capable of producing mycelium-based biomaterials with higher compressive strength and improved stiffness properties. The study attributes this behaviour to the species' ability to rapidly colonise a wide range of organic substrates, supported by its relatively thick cell wall structure.

*Pleurotus ostreatus*, commonly known as the oyster mushroom or "white oyster", is one of the most widely cultivated mushroom species globally and is frequently used in mycelium-based material research. The species was also observed to develop a

denser outer skin and a more rigid material structure compared to several other fungal species. Due to these characteristics, the study identifies *Pleurotus ostreatus* as one of the preferred fungal species for producing mycelium-based biomaterials and composite systems.

Consistent with these findings, Voutetaki and Mpalaskas (2024) demonstrate that the addition of bamboo fibers up to an optimal content increase both the density and mechanical strength of MBCs. Thus, reinforcing the notion that substrate choice plays a pivotal role in MBC's structural performance.

### 2.1.2. Adhesion characteristics: Fungal growth and hyphal network formation

The fabrication of the various MBCs follows a consistent methodological process. During substrate inoculation for nutrient, the fungus produces mycelium, a highly interconnected network of filamentous structures known as **hyphae**. These elongated fungal cells bind the particulate components of the substrate, resulting in a mycelium-bound composite. When fungal growth occurs on a lignocellulosic substrate, the hyphae develop into a **porous, interconnected network** that mechanically binds the substrates together. The adhesive performance of the mycelium composite is governed by key variables, including **fungal species selection, substrate composition, and processing conditions**, which collectively influence the binding efficiency and structural integrity of the material. Additionally, fungal species have growth rates and environmental requirements, which further influence mycelium development and mechanical performance. (Voutetaki & Mpalaskas, 2024)

## 2.2 Optimum MBC recipes

The standard fabrication process for MBCs involves three main stages following substrate preparation and sterilisation: (1) **inoculation** of the substrate under controlled conditions; (2) **incubation** for a period of 7 to 30 days, depending on the fungal species, under regulated humidity, temperature, and ventilation; and (3) **thermal deactivation treatment** of the fully colonized material to terminate biological growth. (Bitting et al., 2022)

### 2.2.1. Growing conditions

Precise control of **temperature, humidity, and nutrient availability** during mycelial growth can significantly enhance its adhesive performance. Incorporating a **vacuum system or intake airflow system** within the incubation chamber can improve **oxygen diffusion** during the inoculation phase. However, maintaining optimal **relative humidity** is critical to prevent substrate desiccation, which would otherwise inhibit mycelial growth and network formation. (Voutetaki & Mpalaskas, 2024)

### 2.2.2. Formwork

Mycelium growth is highly sensitive to environmental conditions, the inoculation and incubation phases are typically carried out within **pre-defined formwork**. The formwork can be designed with **customised geometries** and sealed to maintain a stable internal environment for fungal growth. For large-scale production, the **reproducibility** of laboratory conditions and the ability to achieve **mass customisation** through mould-based fabrication are critical for the consistent manufacturing and application of MBCs. (Bitting et al., 2022)

### 2.2.3. Assembly

Assembly systems vary depending on whether the mycelium is treated as a solid material block or as a lightweight panel integrated within a supporting frame. Earlier assembly methods involved growing

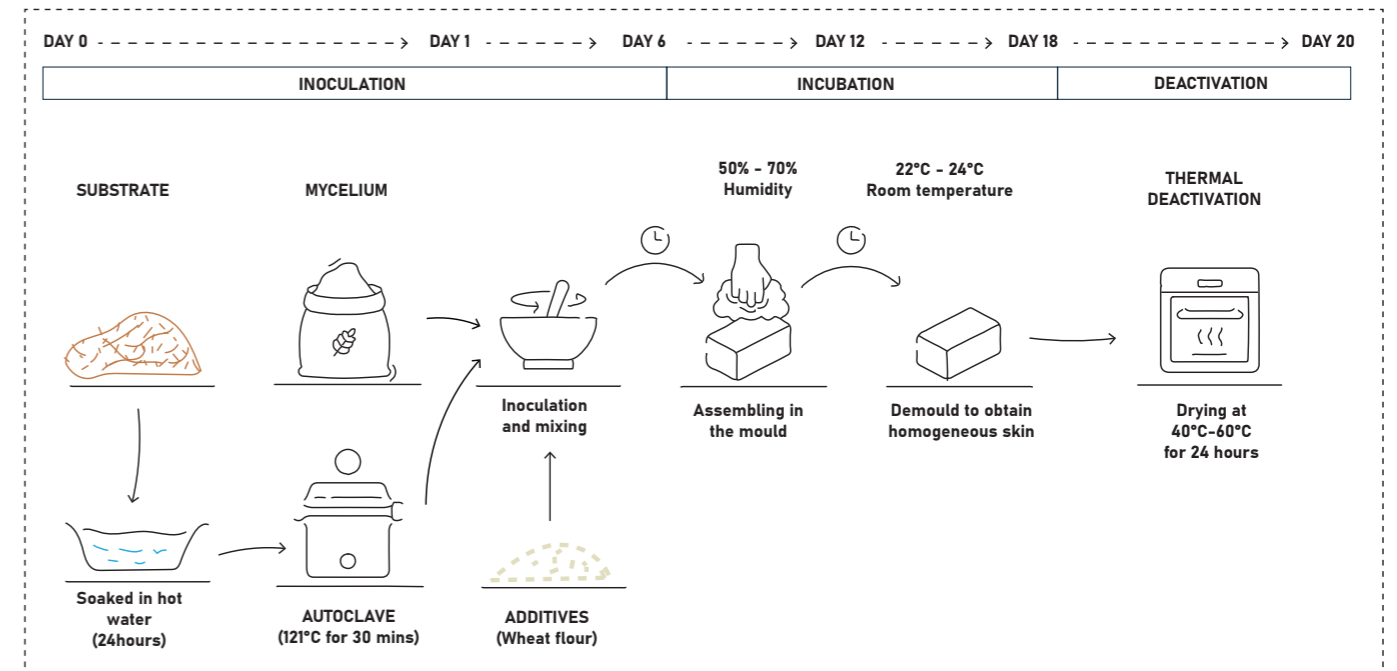


Figure 05: MBC production recipe (Author)

individual mycelium modules separately, drying or baking them, and then joining them to timber plates or backing grid systems. In some cases, multiple mycelium blocks were assembled using interlocking forms or external support structures. Other case studies use timber frames to connect and stabilise mycelium panels, where the mycelium acts as an infill or panel material rather than a standalone structural block. One of the example is the Hy-Fi project by The Living and Ecovative. In this project mycelium bricks were grown in moulds, dried and stacked together. It was similar to brick masonry, to form circular towers. Another example is The Growing Pavilion, presented at Dutch Design Week, where mycelium-based panels were attached to a timber-frame structure. In this project, the timber frame carried the structural load while the mycelium panels functioned as lightweight wall and surface elements.

An increasingly popular assembly method known as “bio-welding” or “myco-welding” involves joining structures composed of modular living components and allowing them to grow together into monolithic assemblies. This process is technically demanding because it requires two distinct growth stages. First, individual units are cultivated from loose substrates within moulds. Second, the living units

are assembled into a predesigned configuration. It is then maintained under controlled environmental conditions for the required days to grow. A further challenge in large-scale myco-welding is the drying and stopping the growth. If this process is not carried out actively, fruiting bodies may develop on the structure, which can be unwanted depending on the intended application and context. (Dessi-Olive, 2022)

Further, a major challenge in construction-scale applications is the difficulty of scaling up mycelium cultivation. Large formworks require strict sterilization and controlled environmental conditions. It also needs continuous air exchange to grow effectively. As a result, most structures are assembled from smaller modular components, with rare exceptions such as the El Monolito Micelio project, which used complex air-injection systems. While alternative approaches such as heat-free sterilisation and the use of non-sterile tolerant species have been explored, large-scale production remains challenging. Another limitation is the need for material compaction or heat pressing within formworks, which often restricts achievable geometries to simpler shapes. It also requires the need for more energy consumption on each component. Its growth can be paused through drying and reactivated when humidity increases. This

property has been explored for applications such as bio-welding and self-healing systems highlighting its potential as a building element. (Ghazvinian et al., 2022)

With respect to finishes after assembly for higher durability, floor tiles produced by the Italian company Mogu uses a topcoat of a water-based paint. It is a protective layer of 67% bio-based polyurethane with oyster shells. The core layer consists of 100% high density fibreboard. (Bitting et al., 2022)

## 2.3 Mechanical behaviour of MBCs

The standard fabrication process for MBCs involves three main stages following

### 2.3.1. Density and porosity

One of the early studies reported that specimens reinforced with 10% natural pineapple fibres exhibited high density and high compressive strength. This indicates a positive relationship between increased density, achieved through fibre reinforcement and enhanced compressive performance. However, this relationship is also affected by additional factors, including **fibre distribution, matrix-to-fibre ratio, and the characteristics of both fibres and matrix materials**. This relationship is complex, as higher porosity or certain internal structural arrangements can sometimes improve the mechanical strength of composites. Therefore, finding the right balance between these factors is important in achieving a favourable result. (Voutetaki & Mpalaskas, 2024)

As shown in Fig. 06, the flexural strength values were similar to the ranges reported in previous studies as the natural fibre (NF) content increased. This indicates that fibre

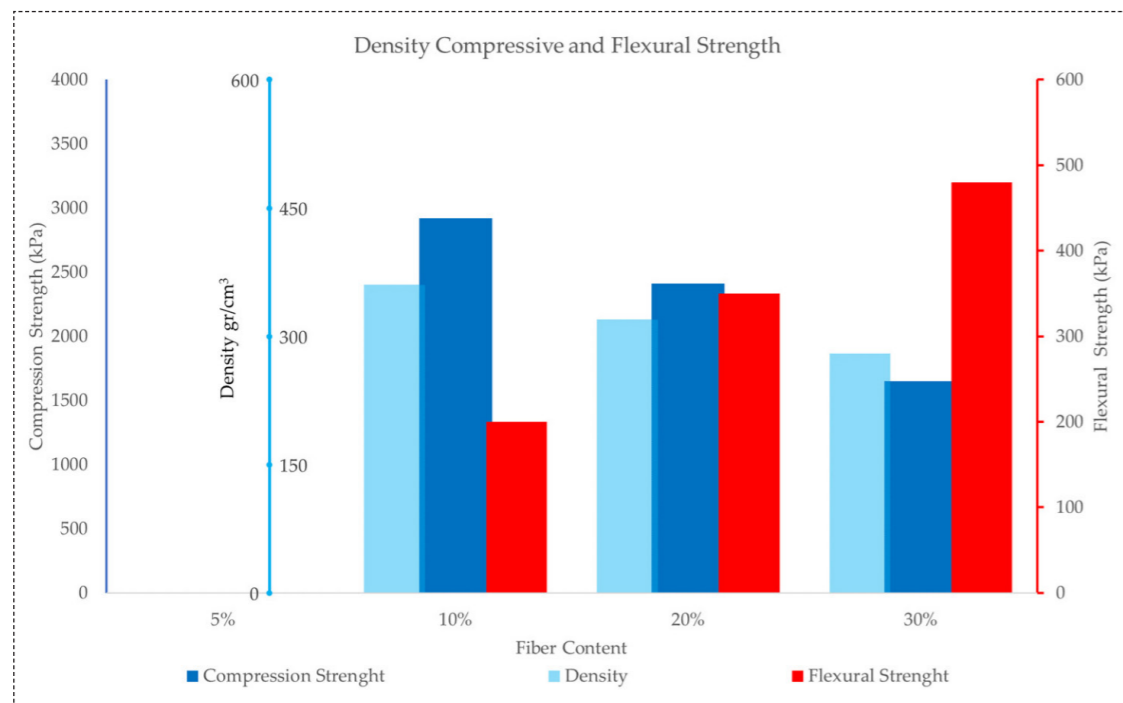


Figure 06: Impact and trend of three different fiber content levels on mechanical properties. (Source: Voutetaki & Mpalaskas, 2024)

Table 03: Compression and flexural strength in different combination of substrates and fungal species (Adapted from K. Aiduang et al., 2022)

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 ( $p \leq 0.05$ ).

reinforcement had a positive effect on the mechanical performance of the composite. At the same time, the compressive strength and density of the material decreased. Therefore, the addition of natural fibres significantly influenced the flexural behaviour of the mycelium composites.

Fibres act as reinforcement within the composite, helping the material resist deformation while distributing stress more evenly throughout the matrix. They also help bridge small cracks within the material, reducing crack propagation and improving strength. The aspect ratio of the fibres also affects their reinforcing performance, with longer fibres generally providing better mechanical interlocking within the composite. In addition, the volume of fibres used is important. Very few fibres may not provide enough reinforcement, while excessive fibre content can lead to stress concentration, which may reduce the overall strength of the material. (Voutetaki & Mpalaskas, 2024)

### 2.3.2. Compressive strength

Compressive strength is a critical characteristic that reflects a material's ability to resist direct compressive loads

commonly encountered in the construction industry. The growth substrate of mycelium significantly influences the material's density. However, one has to keep in mind that the fibrous substrates that produce a denser mycelial network do not necessarily improve the binding quality that is significant, which is a key factor in achieving high compressive strength. Predictive modelling has also been applied to establish relationships between compressive strength and split tensile strength, demonstrating that fibre type and fibre ratio strongly influence mechanical performance. Table 03 contributes to some precursor values of the MBCs and they are still not close enough to reach the market benchmark values to be used in load-bearing structural applications. (K. Aiduang et al., 2022)

### 2.3.3. Tensile strength

Tensile strength is described as a material's resistance to deformation under bending loads. Fibre-reinforced materials (FRMs) are known for their high tensile performance, which results from the combination of a flexible matrix and high-strength reinforcing fibres. This makes them suitable for a wide range of structural applications. This also helps in allowing for exploration in

**compression-focused reinforcement forms.** (Voutetaki & Mpalaskas, 2024)

Fibre orientation affects the direction and amount of reinforcement within the material. Adding fibres such as bamboo can improve flexural strength by providing additional support within the matrix. Fine fibres also help improve the distribution of the material and create better bonding with the mycelium network, which improves the overall structural performance of the composite. The study also explains that a more uniform composite, achieved through even distribution of mycelium and reinforcing materials, improves flexural performance by distributing stress more evenly throughout the material. In addition, the chemical and physical bonding between the mycelium matrix and the reinforcing fibres or substrates plays an important role in resisting bending forces. (Voutetaki & Mpalaskas, 2024).

#### 2.3.4. Limitations of load-bearing MBCs

Despite extensive research on natural fibre treatments and substrate modifications with different materials, the literature does not identify a straightforward method for significantly enhancing the mechanical properties. This is largely due to the complex characteristics of bonding between the mycelium species and the fibrous substrate type.

Factors such as **porosity, filler fibre substrates and reinforcements** influence the relationship between density and compressive strength in MBCs. Higher density of high-strength reinforcements can lead to significant improvements in compressive performance. Adjusting the ratio of the reinforcing fibre further influence the relationship between density and compressive strength by affecting load transfer, structural integrity and crack resistance within the material. This in turn produces stronger fibre-reinforced mycelium composites, yielding higher compressive strength values compared to studies that have alternative materials

or fabrication techniques. (Voutetaki & Mpalaskas, 2024)

Another point being, most load-bearing structures made from **MBCs rely on compression-only forms** to compensate for the material's low performance under compressive and bending stresses. The material does not hold capacity to bear compressive stresses. Also, mycelium is largely grown using **inorganic formworks, such as plastic moulds**, which are often discarded after use, raising concerns about material waste.

# 3.0

## Role of substrate selection in mechanical performance

### 3.1 Function of substrates and additives

The substrates are used to maximise the growth of mycelium. They consist of lignocellulosic materials that are procured from agricultural crop waste, such as, but not limited to, cotton, corn, flax, hemp, and wheat. These substrates, depending on their nutritional profile, affect the density of the material. A higher proportion of grain typically corresponds to a higher material density. Depending on the desired material profile and field of application, the use and customisation of substrates can be tailored to achieve the desired properties in the final material (Bitting et al., 2022).

Additives are supplementary materials added to the substrate to support and improve

mycelial growth. They provide additional nutrients and enhance the bonding between the substrate particles. In one of the studies (Table 04) of a Jute jacketed prototype (to check for tensile performance) by Amudhan et al. (2025), Wheat flour (A1) was selected for its ability to stimulate mycelial growth through its cellulose and hemicellulose content. It also proved to be one of highest in mean compressive strength of 0.88 MPa in comparison to no additives or other. In addition, GROWN.bio also recommends the inclusion of flour in their substrate as a growth accelerator for mycelium. Guar gum (A2) was selected for its natural binding properties, which increase substrate viscosity and moldability, thereby providing improved structural integrity. Papier mache (A3) was chosen because paper pulp and paper fibre aggregates enhanced the viscosity of mycelium substrate pastes while simultaneously improving their mechanical performance.

### 3.2 Lignocellulosic substrate growth types and its characteristics

In one of the experiments by Nguyen et al., the growth behaviour of mycelium was influenced by the type of outer skin material used during fabrication. In experiments (Fig. 08) using hemp sheets, the dense arrangement of randomly oriented **hemp fibres retained high levels of moisture, which supported consistent mycelial growth throughout the specimen.** Due to this moisture retention, the mycelium



Figure 07: Results of growth on different skin materials. Hemp sheets (left), jute sheets (middle) and knitted hemp rope (right). (Source: Nguyen et al., 2022)

was able to grow beyond the boundaries of the mould and along the outer edges of the hemp sheets. The **dense growth also reduced separation during shrinkage and resulted in a stiffer and more successfully bonded composite system.** The hemp sheet effectively acted as a “soft mould”, where the natural fibre layer remained integrated within the final material system.

In comparison, experiments using woven jute sheets showed lower performance. The lower thickness and density of the **jute fibres were unable to retain sufficient moisture,** causing the specimens to dry before enough mycelial growth could occur. This resulted in uneven shrinkage and separation between the substrate and the outer skin layer.

Similarly, experiments using knitted hemp rope as the outer skin also faced difficulties. The loose knitted structure deformed during compression of the substrate into the mould. Moisture retention insufficient similarly, resulting in weaker and uneven mycelial growth. Due to the uneven distribution of the substrate and lower structural rigidity, the final composite showed limited success.

As per Fig. 08 experiment, the mycelium substrate is pressed into a thin, rigid sandwich panel between two layers of hemp mat. The dense hemp fibers help maintain a consistently moist environment, which supports mycelium growth. No separation is observed between the substrate and the hemp layers. This configuration produces the stiffest sample. Consequently, in Fig. 08, loose hemp fibres are used instead of compressed hemp mats, and rattan reinforcement is placed within the mycelium substrate. The randomly oriented loose fibres allow for greater airflow, creating more space for mycelium growth. This results in a sample that remains stiff but also shows higher elasticity. The rattan functions as a structural reinforcement and bonds effectively with the mycelium, leading to a significant increase in overall stiffness.

### 3.3 Substrate-driven mechanical optimisation

Selecting substrates with high cellulose, hemicellulose, and lignin content can improve interfacial bonding between the

Table 04: Comparison in the performance of different additives (Adapted from Amudhan et al., 2025)

Index	Type	Mean Density (kg/m <sup>3</sup> )	Mean Volume Shrinkage (%)	Mean Weight Shrinkage (%)	Mean Compressive Strength (MPa)
Test A	NA	386.20 (18.37)	31.91 (3.31)	67.61 (0.42)	0.63 (0.07)
Test A	NA.2	390.44 (19.27)	44.95 (2.42)	71.24 (1.30)	0.44 (0.06)
Test A	A1	414.97 (9.76)	37.37 (1.46)	65.20 (0.15)	0.88 (0.07)
Test A	A1.2	410.38 (20.33)	41.80 (3.99)	68.34 (0.72)	0.52 (0.05)
Test B	A2	394.07 (15.65)	26.07 (4.56)	63.05 (0.70)	0.27 (0.07)
Test B	A3	456.95 (11.52)	35.41 (1.94)	61.44 (0.67)	0.47 (0.06)

NA: No Additives; NA2: No Additives; A1: 10% Wheat Flour; A1.2: 10% Wheat Flour; A2: 10% Guar Gum; A3: 10% Paper Mache



Figure 08: Results of growth on different composites. Multilayer composite (left), hemp mat sandwich (right) (Source: Nguyen et al., 2022)

mycelium and the substrate, leading to better binding efficiency and improved mechanical performance of the composite material (Manan et al., 2021).

The targeted placement of material within structural systems can help optimise the strength-to-weight ratio of mycelium composites, allowing their use in larger architectural applications despite their relatively low natural compressive strength. These approaches aim to make use of the lightweight nature of mycelium while reducing its structural limitations for construction use. Strategic material placement involves designing the layout, orientation, and geometry of the mycelium composite based on specific structural requirements. Mycelial growth can also be **guided in preferred directions so that the fibrous network aligns with the main stress paths within the structure**, improving both tensile and compressive performance. This behaviour is similar to grain orientation in wood, where the material performs better parallel to the grain than perpendicular to it (Voutetaki & Mpalaskas, 2024).

# 4.0

## Existing methods of enhancing structural capacity

### 4.1 Densification and pressing techniques

A study by Bitting et al. (2025) demonstrates the applicability of creating a mixed-density mycelium. The composite is created by combining high-density MBC in the outer layer with a low-density infill MBC at the

core. After growing the high-density MBC and low-density infill MBC separately, they were transferred into a mould together so that mycelium could grow and combine them without additional binders to preserve the material's circularity. This process is commonly known as bio-welding. The mould was then left in the climate chamber to grow for one to two weeks, then removed and baked at 60°C until the weight stagnated. It evaluates different densification techniques, namely (Table. 05), cold pressing (CP), heat pressing (HP), baking and moisture reconditioning through soaking. Heat-pressed composites exhibited the highest structural performance. Substrates were ground to approximately 8 mm fibre length, mixed with bran and water, sterilised via autoclaving, and incubated at 26°C and 65% relative humidity.

Hot-pressed (HP-MBC) was pressed at a high pressure (4–6 MPa) and its processing temperature being 120°C. CP was pressed at a medium (2–4 MPa) to high pressure,

Table 05: Tested results comparison of HP & CP (Adapted from Bitting et al., 2025)

Iteration	Length (mm)	Width (mm)	Height (mm)	Dense Material Type	Pressure	Substrate	Average Fmax (N)
1	40	40	80	CP	medium	rapeseed	16.8
1	40	40	80	CP	medium	hemp	17.03
2	25	25	80	HP	medium	hemp	30.3
2	25	25	80	BW	-	-	13.72

1 low:(0-2 MPa), medium:(2-4 MPa), high:(4-6 MPa)



Figure 09: Two cold-pressed mixed-density module grown at 1:1 scale, approximately 400mm in width, 60mm in thickness and 100mm in height. Stacked to illustrate assembly concept (Source: Bitting et al., 2025)



Figure 10: (left) Assembly of CNC-cut grid components through jointless, slit-and-slot connections and wooden dowels, (right) MycoTree is the centrepiece of the "Beyond Mining - Urban Growth" exhibition at the 2017 Seoul Biennale of Architecture and Urbanism in Korea. (Source: Heisel, 2017)

and were then immediately ready for use or could be baked in an oven (CPB).

In Iteration 2, HP-MBC samples reached an average maximum pull force (Fmax) of approximately 30.3 N, whereas beech wood samples achieved only 13.72 N. This indicates that material continuity within mycelium-based systems enhances interfacial strength, likely due to improved hyphal integration between infill and dense MBC components.

**Cold-pressed MBC (CP-MBC) demonstrated better biological performance** during secondary growth, as the **material retained sufficient moisture** to support mycelial regrowth without additional conditioning. The experimental results demonstrate that mycelium-to-mycelium bonding is strong. Pull-apart tests showed that samples using densified mycelium boards achieved higher and more consistent maximum force values than those bonded to beech or pine wood. The binding strength of MBCs indicates their suitability for the flexibility of these materials in terms of design and fabrication. By modifying wall geometries to incorporate infill MBCs as acoustic dampening elements, the performance of mixed-density mycelium modules can be more effectively utilized. Fibre length can be adjusted to achieve a more porous structure, while the growth period can be modified to influence pore connectivity.

### 4.2 Geometric optimisation

MycoTree (Fig.) is an experiment of a spatial branching structure composed of load-bearing mycelium components. The geometry was developed using 3D graphic statics to achieve a compression-only structural form. 3D graphic statics is a method developed by Block Research Group at ETH Zurich that aids in extending the 2D structural design technique to spatial systems. It uses mycelium with bamboo as its primary material.

The components were designed to support their own weight and the weight of the grid mainly through compressive loading. The grid structure functions in tension, stabilizing the branching members and preventing structural failure. For this reason, the grid was fabricated from 8 mm thick CNC-cut bamboo composite boards developed at the Future Cities Laboratory (FCL) for high tensile and bending resistance. Bamboo members were also used as linear structural elements due to their lightweight properties and compressive strength, while steel connectors were incorporated at the joints to improve stability and assembly accuracy.

To simplify on-site assembly, the grid joints were connected using slit-and-slot systems secured with locking elements and wooden dowels. The structure was able to resist a horizontal point load of 0.7 kN applied at a height of 1.27 m. However, since the system was designed primarily for compression loading, horizontal forces were minimized

to maintain structural stability. The project demonstrates how regenerative materials combined with structural design can provide an alternative to conventional building materials (Heisel, 2017).

### **4.3 Limitations of current methods**

Existing methods used to improve compressive strength, such as hot pressing (HP) and cold pressing (CP), often require high energy input while providing limited improvement in mechanical performance. These methods can also reduce the natural porosity of the material, affecting insulation properties and air flow within the composite. In some cases, excessive pressing may damage the mycelial network and weaken internal bonding. Thickness limitations during growth can increase the risk of internal contamination, while uneven pressure distribution during pressing can lead to inconsistent density and variable structural performance between samples. Drying also becomes difficult in large in-situ structures, such as arches, which cannot be easily placed inside industrial ovens for deactivation. Further development is required to improve the consistency and structural reliability of MBCs.

# 5.0

## Structural applications (Case studies)

The transition from material to architectural application was an important start to the process of evolving the built environment and introducing new techniques to the world. Phil Ross and Sophia Wang, co-founders of MycoWorks, are among the key contributors to the field. They helped bring wider attention to the use of fungi-based materials in the architectural world. In 2011, they exhibited series called *Mycotecture*. It consisted of architectural elements like vaults, wall sections and structural installations made from interlocking

mycelium composite bricks. This exhibit demonstrated the versatility of mycelium as a building material. Since then a number of experimental architectural projects have been exploring mycelium-based materials to develop as a structural material (Almpani-Lekka et al. 2021).

The reviewed case studies are summarised in Table 06 by Almpani-Lekka et al. (2021), which classifies each project according to its construction environment, the type of mycelium component used, the fungal strain, substrate mix, supporting structural system and post-treatment method. They demonstrate structural strategies that inform and support the objectives of this research. Eventually, these precedents serve as valuable references for new applications of mycelium in load-bearing and architectural systems (Almpani-Lekka et al. 2021).

### 5.1 Interlocking and modular components

The case study by Tseng et al. (2024) (Fig. 11) focused on designing and building a barrel vault composed of modular interlocking components using bamboo composite



Figure 11: Proposed interlocking mechanism (left), Click brick arch (middle) and principle circular stress line (right). (Source: Tseng et al., 2024)

material. This is based on compression-dominant arch principles. Further, it discusses how **material geometry and modularity can be used to achieve favourable compressive behaviour results** for MBCs. The module design assumed the **minimum thickness for mycelium growth to be 3cm**. The mechanism could assemble both the vertical and horizontal units. This study only demonstrates the successful cultivation and incubation of the mycelium with bamboo at specific mixing ratios. To fully assess the structural performance, a 1:1 module needed to be fabricated and subjected to mechanical testing to evaluate the behaviour of individual units. **Manufacturing tolerances remained a critical consideration** to further optimise the standard operating procedures for reliable production.

### 5.2 Monolith structural assembly

The monolithic case study by Dessi-Olive (2022) explored the development of large-scale mycelium structures using monolithic construction methods. The

research focused on growing continuous self-supporting forms using reusable wooden and textile formwork systems. The project aimed to achieve more precise geometries while reducing the need for multiple discrete components. Bio-welding/myco-welding techniques were used where separate living mycelium panels or blocks were joined together through continued fungal growth to form larger monolithic assemblies without additional adhesives. (Fig. 12) Reusable formwork was identified as both an important design tool and a major limitation, as large-scale growth requires controlled ventilation, sanitation, demoulding, and drying conditions. The research concluded on the fabrication and scalability challenges associated with large monolithic applications.

### 5.3 Reinforced and laminated with bio-welding

Wisniewska, Boghossian, and Heisel (2025) investigate the development of MycoPly, a laminated MBC system designed to

Table 06: Comparison of built projects exhibiting ways of structural applications with different substrates and fungus type (Source: Almpani-Lekka et al. 2021)







Project / Year of completion	Location	Type	Structure	Fungus	Substrate	Post-treatment	Creators
 HY-FI (2014)	Outside	Brick	Wood, Steel	<i>Ganoderma lucidum</i>	Corn stalks	Heat treated	The Living Studio
 SHELL MYCELIUM (2017)	Outside	Panel	Wood, Steel	Information not available	Coir pith	Naturally dried	Studio Beetles 3.3 Yassin Arredia Design
 MYCOTREE (2017)	Inside	Block	Bamboo, Steel	<i>Pleurotus ostreatus</i>	Sugar cane, Cassava root	Heat treated	Sustainable Construction KIT Karlsruhe Block Research Group ETH Zürich
 MONOLITO MICELIO (2020)	Outside	Monolith	Wood, Steel	<i>Ganoderma lucidum</i>	Hemp	Naturally dried	Georgia Institute of Technology School of Architecture
 GROWING PAVILION (2020)	Outside	Panel	Wood	<i>Ganoderma lingzhi</i>	Hemp, Cattail, Mace	Heat treated, Weather resistant biocoating	Company New Heroes E. Klarenbeek
 MY-CO SPACE (2021)	Outside	Panel	Wood, Steel	<i>Fomes fomentarius</i>	Hemp	Heat treated, Weather resistant coating	MY-CO-X Collective



Figure 12: Installation of the prototype onsite (Source: Dessi-Olive 2022)

overcome the structural and scalability limitations of conventional mycelium materials. The study aims to demonstrate that this can be achieved through controlled densification and bio-welded lamination.

During experiment A & B, samples were produced using different ratios of corn-based substrates and hemp hurd, while densification was achieved through either cold pressing before dehydration or hot pressing after dehydration. These variations allowed the authors to assess how substrate composition and pressing sequence affect compressive, tensile, and bending behavior. The results showed that the highest bending strength was achieved using a balanced 50:50 corn-hemp mixture with cold pressing. These findings demonstrate that **densification strategy directly influences the dominant load-bearing behavior of the material**. To further enhance structural capacity, the authors developed MycoPly, a laminated system made from thin 12 mm MBC sheets that are bio-welded together using active mycelium. This bio-welding process fuses the mycelial “skins” of each layer, creating thicker panels (24 mm, 48 mm, and 72 mm) with improved stiffness and load distribution. The laminated structure benefits from better oxygen access during growth, more homogeneous mycelial networks, and increased structural reliability compared to monolithic thick MBC elements.

In conclusion, the study demonstrates that **thin-layer lamination improves oxygenation, growth homogeneity, and mechanical performance**. It also discusses the possibility of mechanical properties being tailored through substrate ratios and pressing methods. Hot pressing enhances compressive strength, whereas cold pressing improves tensile performance, enabling material behavior to be tuned for specific structural applications. The use of bio-welding allows for strong, synthetic binder-free lamination of MBC layers. Finally, MycoPly panels performed successfully in the full-scale outdoor prototype MycoShell (Fig. 13) for six months with minimal degradation.

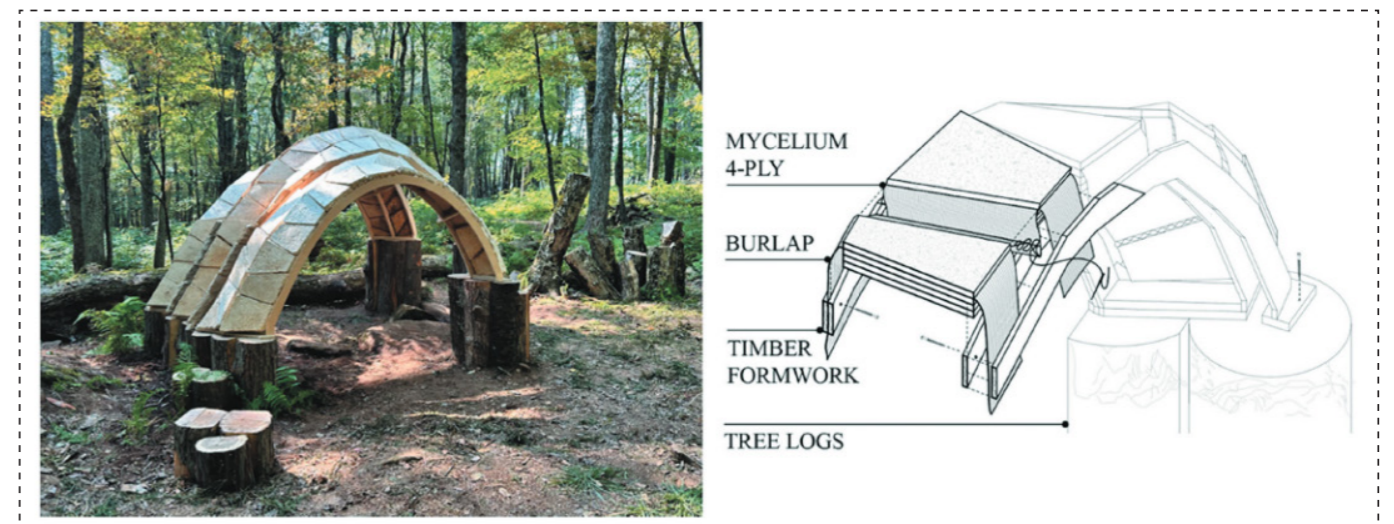


Figure 13: Image and detail drawing of MycoShell at Bethel woods, NY (Source: Wisniewska et al., 2025)

# 6.0

## Introducing: Scaffolding reinforcement strategies

### 6.1 Concept: 3D printed porous scaffold

A recent study by Sharma & Le Ferrand explored the use of a stiff reinforcement scaffold as a structural substrate for mycelium growth. The research highlighted the importance of a pre-defined architecture, particularly in terms of porosity and density, to support uniform mycelial colonisation.

The fabrication process involved coating a porous 3D-printed wood-PLA scaffold with a nutrient-rich additive solution to encourage mycelial growth. The study showed that the growth behaviour of the mycelium depended on factors such as unit cell size, scaffold porosity, and the Peptone-Malt-Agar (PMA)

coating (Fig. 14). Unit cell sizes between 5–25 mm and porosity ranges between 50–90% were systematically tested through multiple iterations.

A gyroid geometry was selected due to its interconnected porous network, large surface area and favourable mechanical behaviour. While the nutrient solution supported biological growth, the 3D-printed scaffold allowed precise control over the porous geometry and structural properties of the composite system.

The study also observed that micropores within the wood-PLA scaffold retained moisture through capillary action, helping maintain conditions suitable for continued mycelial growth and metabolic activity. *Ganoderma lucidum* was selected as the fungal species due to its established material performance.

The research concluded that the interaction between the scaffold's macroporosity and the material's microporosity improved mycelial colonisation, which contributed to better mechanical strength and overall composite performance (Sharma & Le Ferrand, 2025).

The scaffold porosity is a critical design parameter that governs the compressive performance of mycelium-based

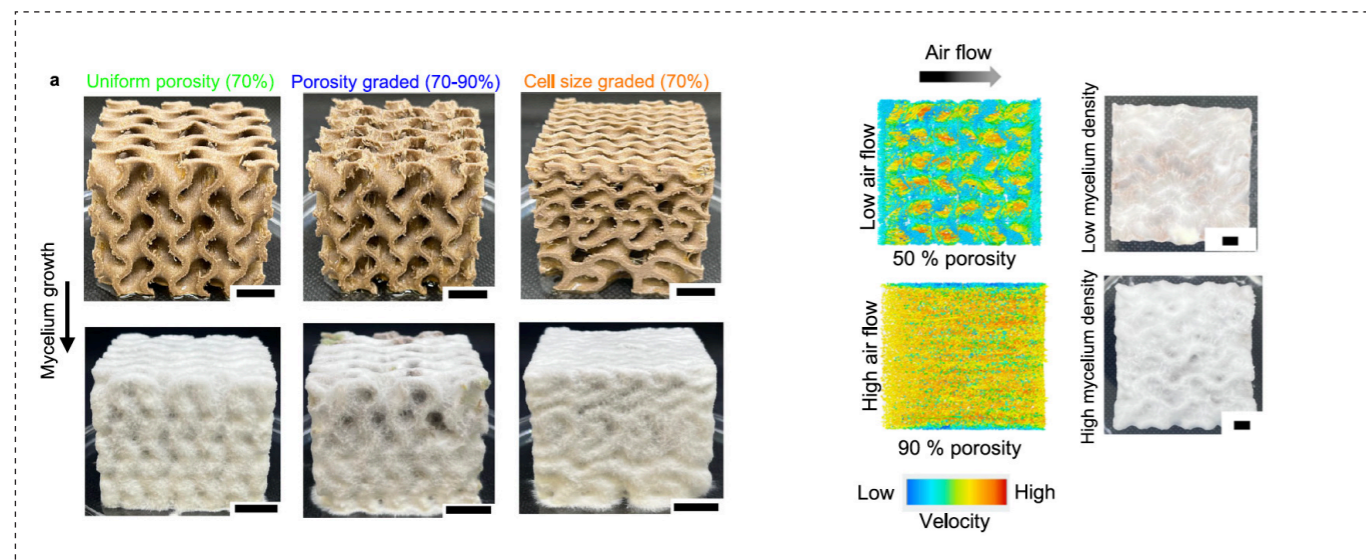


Figure 14: (left) 3 different scaffold porosity types showing 21 days of growth; (right) Difference of the air flow in 50% and the 90% unit cell porosity scaffold (Source: Sharma & Le Ferrand, 2025)

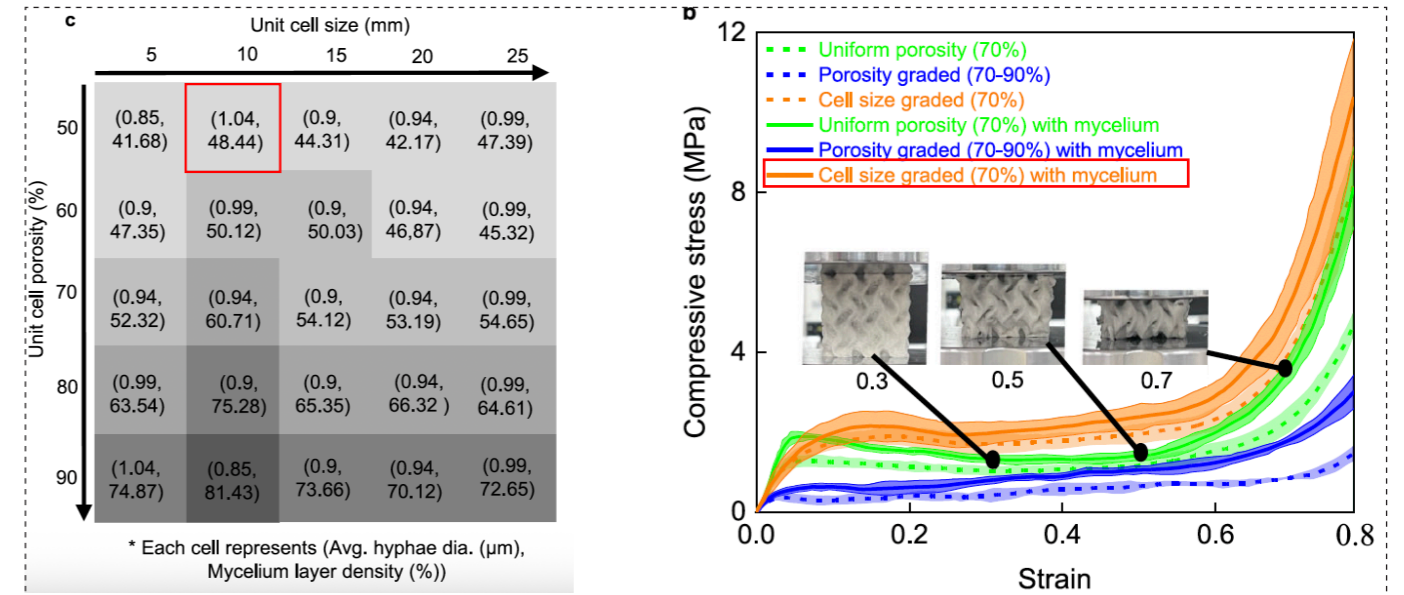


Figure 15: (left) Representation of the change in average hyphae diameter and mycelium density with change in unit cell size and porosity (right) Stress-strain curves of the results with varied porosity (Source: Sharma & Le Ferrand, 2025)

composites (MBCs). Scaffolds with lower porosity consistently showed higher elastic modulus, yield strength, and peak strength because they had thicker load-bearing walls and greater structural continuity. As the porosity increased, the mechanical strength of the scaffolds decreased, since the thinner walls were more likely to collapse under compression.

However, mycelium colonisation significantly improved the mechanical performance of all scaffold designs, particularly after the structural cell walls began to collapse under compression. In highly porous structures, the mycelium acted as a foam-like reinforcement, bridging voids and contributing to load transfer, which resulted in large percentage improvements in yield strength and energy absorption.

The best-performing case was the cell-size graded scaffold with 50% porosity (CG50\_my). This design achieved elastic modulus (E) of  $257 \pm 18.8$  MPa, Yield strength ( $\sigma_y$ ): of  $7.29 \pm 0.65$  MPa, Peak strength ( $\sigma_p$ ) of  $15.77 \pm 1.08$  MPa, Specific energy absorption (SEA) of  $8.79 \pm 0.77$  kJ/kg

This superior performance is attributed to the lower porosity, which provided thicker and stronger cell walls for load bearing, combined with the cell-size grading, which

promoted progressive, layer-by-layer deformation. This deformation mechanism delayed sudden structural failure, improved stress distribution throughout the scaffold and allowed the mycelium network to continue reinforcing the structure after the initial collapse of the cell walls. As a result, CG50\_my showed both high compressive strength and strong energy absorption performance, making it the most mechanically effective configuration within the study.

Another study by Soh & Le Ferrand (2023) further demonstrated the importance of porosity in improving the mechanical performance of mycelium-bound composites. Their research on porous woodpile scaffold structures (Fig. 16) showed that increased porosity improved oxygen diffusion throughout the core of the material, resulting in denser and more uniform mycelial growth. The study found that the formation of dense internal mycelium skin significantly increased the stiffness of the composite system.

The porous scaffold system also enabled the mycelial hyphae to grow through the gaps between the structural elements and mechanically bind the substrate together. Through this interconnected network, the mycelium formed a stronger internal bonding

matrix around the bamboo-based scaffold. The study reported that the stiffness of the porous woodpile structures increased by up to six times after 28 days of growth due to improved airflow and higher mycelium density. The research therefore validated the role of porous internal reinforcement systems in improving compressive stiffness (Fig. 15) and structural behaviour in mycelium-based composites. (Soh & Le Ferrand, 2023)

### 6.3 Concept: Rattan framework

Another study (Fig. 17) investigates the use of a rattan skeleton as a reinforcement system in a prototype stool, termed *Mycomerge*. In this system, the rattan framework functions as an integrated structural element onto which the fibrous reinforcement and mycelium substrate are applied for mycelial growth. The rattan framework functions as the outer load-bearing skeleton, while loose hemp fibres act as flexible intermediate layers through which the mycelium can grow and mechanically bond to the structural frame. A pre-grown mycelium substrate forms the core of the composite, which is subsequently encased with additional loose hemp fibres. Before assembly, both the hemp fibres and the rattan rods were sterilised via steaming or boiling to prevent contamination. To further enhance mycelial growth, flour is incorporated into the fibre matrix as a supplementary nutrient source. Psyllium husk is incorporated into the substrate to improve material distribution,

imparting a clay-like consistency. This design strategy aims to maximise material efficiency while achieving the required load-bearing capacity with a minimal quantity of material (Nguyen et al., 2022).

As per the results, the mycelium exhibited effective binding with all composite components. Substantial growth was observed along the vertical rattan members, particularly within the capillary channels of the rattan structure. This behaviour is because of the capillary effect, which facilitates the transport of water, nutrients, and mycelial biomass throughout the full length of the members. The increased moisture content within the rattan rods and the surrounding wet hemp fibers contributed to improved tensile performance of the mycelium-based rattan-reinforced composite, although the system overall performs most efficiently under compressive loading. Beyond its load-bearing function when integrated with mycelium, the rattan framework also plays a critical role in preventing uneven shrinkage during both the growth and drying phases. Compared to earlier studies, this prototype demonstrates complete adhesion between the substrate and the external skin materials, with no visible signs of separation. **The densely woven rattan base support effectively retains the substrate and prevents structural breakage.** The final prototype (Fig. 18) has a mass of 3.7 kg and is capable of supporting loads exceeding **20 times its own weight**, indicating strong

structural performance and potential for upscaling. (Nguyen et al., 2022)

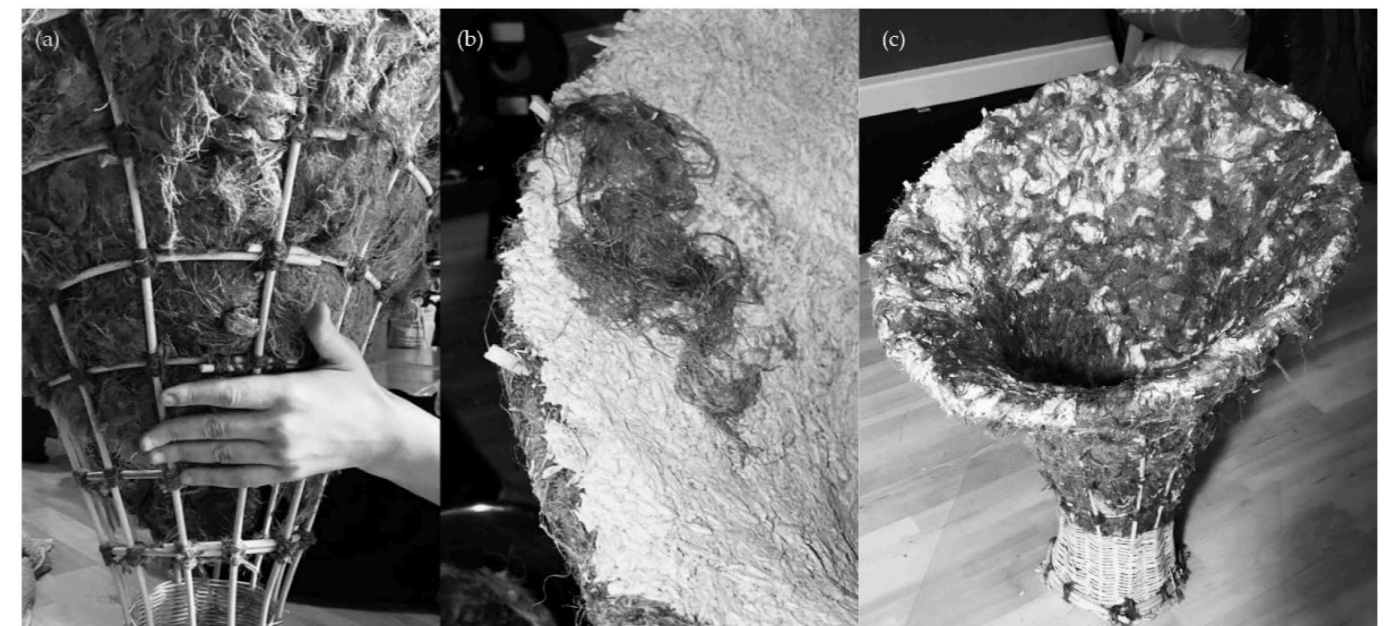


Figure 17: Assembly of the substrate on the Rattan framework (Source: Nguyen et al., 2022)

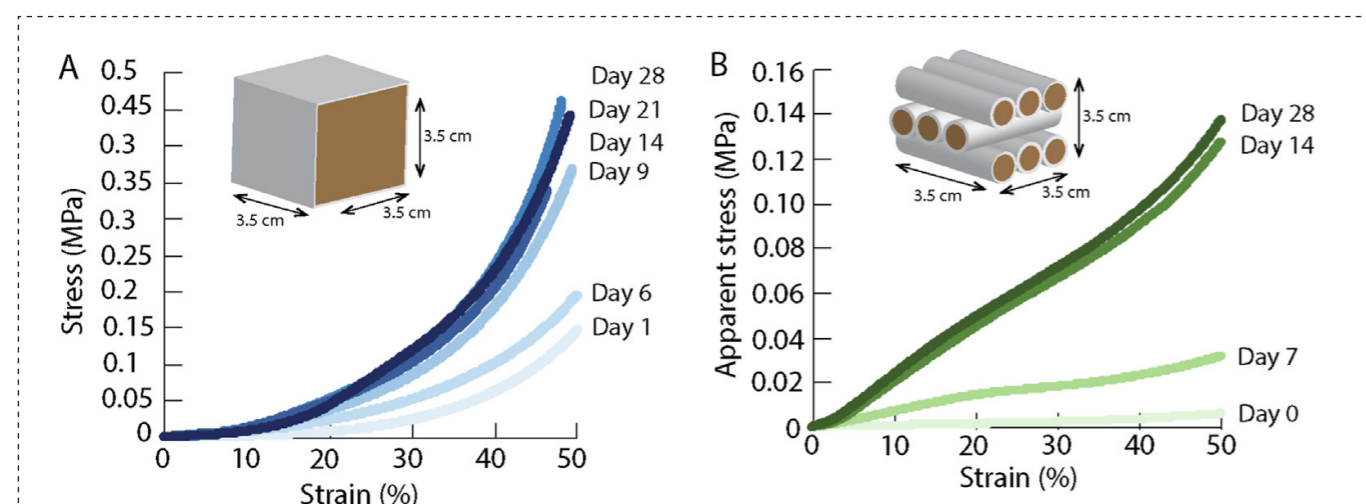


Figure 16: Comparison of compression of blocks and woodpile structures; (left) Stress-strain curves of block composites (right) Stress-strain curves of the woodpile samples (Source: Soh & Le Ferrand, 2023)



Figure 18: Mycomerge: Final prototype (Source: Nguyen et al., 2022)

# 7.0

## Reinforcement form-finding strategy

### 7.1 Lattice scaffolds

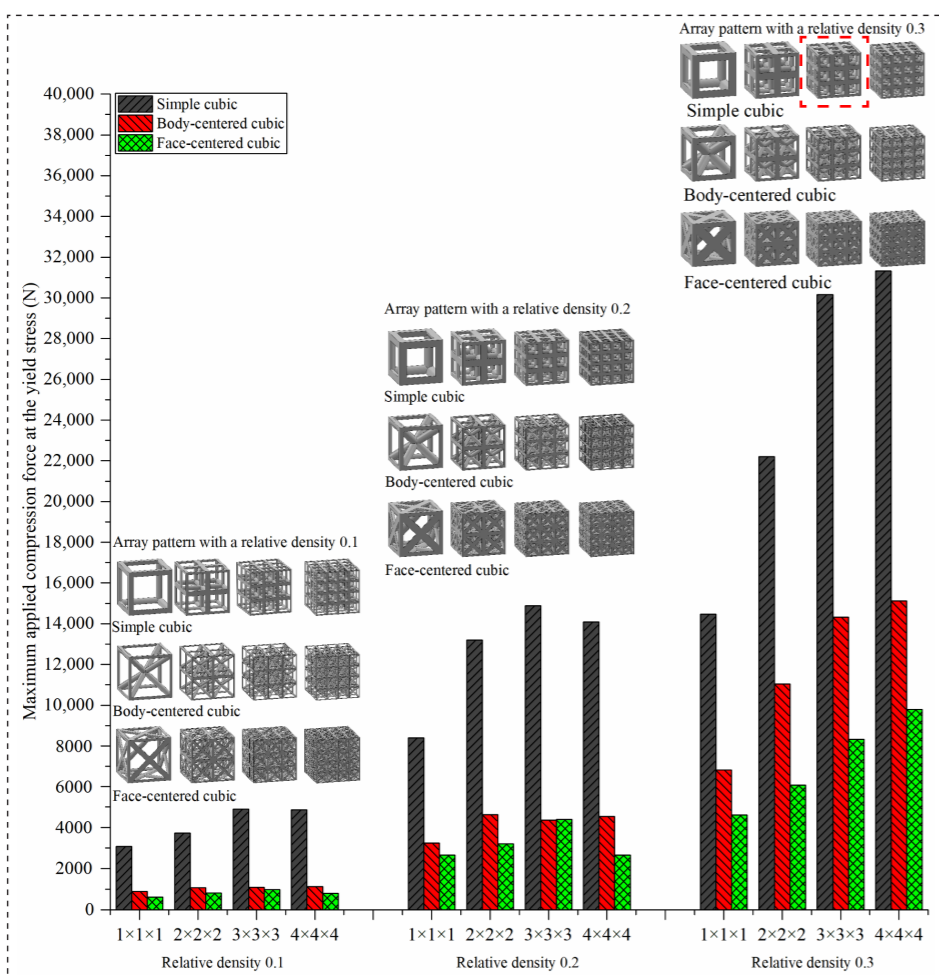
The study by Park et al. investigated the mechanical behaviour of additively manufactured lattice structures under axial compression. The research focused on the influence of unit cell typology, relative density and cell arrangement on

compressive performance. Among the eleven unit cell types tested, the simple cubic, octahedron, truncated cube and truncated octahedron geometries showed the highest compressive strength under the same relative density conditions.

The study also found that lattice structures arranged in a **3x3x3 configuration (Fig. 19) provided an effective balance between compressive strength and density.** In addition, stress concentrations around sharp edges were observed to reduce the load-bearing performance of the structures. On the other hand, geometric optimisation methods such as filleting significantly improved strength. The research provides

**Table 06:** Close to 6 times increase in the yield force with 0.3 relative density (Source: Park et al., 2021)

Relative Density	Simple Cubic			
	1 × 1 × 1	2 × 2 × 2	3 × 3 × 3	4 × 4 × 4
0.1	3070	3715	4890	4860
0.2	8400	13,200	14,880	14,095
0.3	14,470	22,200	30,160	31,315



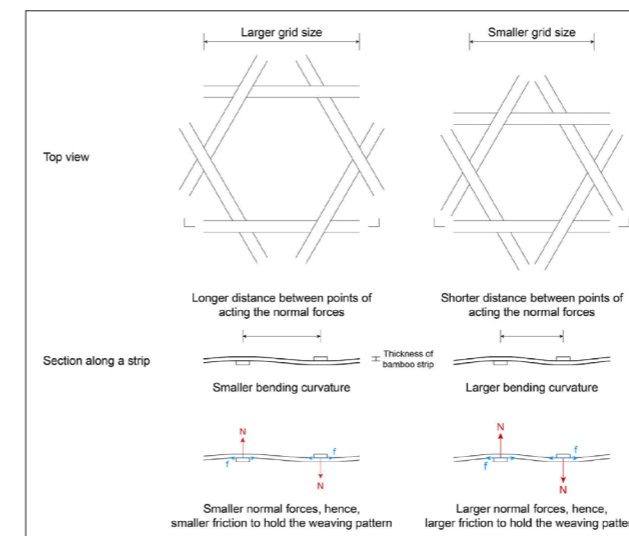
**Figure 19:** Yield force of the lattice structures with different relative densities & cell arrangements (Source: Park et al., 2021)

useful design guidelines for optimising lattice structures for compression-based applications (Park et al., 2021).

### 7.2 Kagome Lattice technique

The structural and formal behaviour of Kagome woven objects is controlled by the relationship between geometric configuration and the material properties at hand. The self-bracing capacity of the system emerges from the friction generated by normal forces at the overlapping contact points of the bamboo strips. This friction is directly controlled by the hexagonal grid size (Fig. 20), which determines the distance between contact points, the degree of bending curvature and the magnitude of the normal forces. This translates to how the cell size grid of the weaving controls the structural performance of the resulting structure.

Within an optimal grid-size range, known as tight interlacing, the woven structure maintains geometric stability without the need for mechanical fasteners. However, because bamboo strips possess inherent bending stiffness and a tendency to straighten, areas of the woven surface located farther from joints tend to flatten. The final form of any Kagome woven object, therefore results from a balance between material behaviour, frictional forces, and the spatial arrangement of joints. This equilibrium-driven process demonstrates



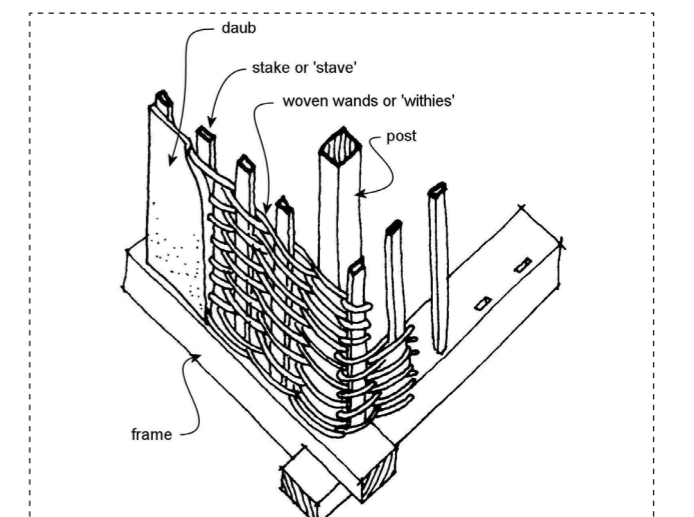
**Figure 20:** Grid size influencing the magnitude of normal forces (Source: Shinohara & Chan, 2024)

that Kagome weaving is a form of structural morphology, where geometry, material and construction technique are a good starting point in shaping the organic forms. Further acting as reinforcement to the building structure as an architectural outcome. (Shinohara & Chan, 2024)

### 7.3 Wattle and Daub wall system

This is a traditional wall construction system consisting of a woven lattice framework known as wattle which is coated with an earthen mixture called daub. The daub is made out of materials like clay, mud, sand, straw and other fibrous materials that improve cohesion and reduce cracking. This construction technique has been widely used in vernacular architecture due to its low cost, availability of local materials, thermal insulating properties and sustainable approach.

Structurally, the system performs efficiently because the woven framework acts as a flexible load-distribution network that transfers forces throughout the wall while preventing localised failure. The woven lattice framework works together in tension and bending, allowing the structure to absorb deformation. Meanwhile, the daub infill contributes compressive resistance, surface stiffness and lateral stability by binding the latticework into a unified panel. This becomes an important example of how binding around a fibre functions structurally within a composite system (Watt, 2015).



**Figure 21:** Wattle and daub building system (Source: Watt, 2015)

# 8.0

## Reinforcement material: Bamboo

### 8.1 Vital substrate

Bamboo is highly preferred in sustainable bio-composite fabrication due to its rapid cultivation cycle, fast renewability and high yield. Incorporating bamboo fibre as a substrate for mycelium growth is fairly a new and experimental research approach and current studies on this topic are still limited. One of the studies by Soh et al. (2020) demonstrated that mycelium can grow successfully on bamboo fibre. In their study, 500 µm bamboo fibres were mixed at a ratio of 70:30 or 60:40 combined with 3 wt% chitosan. The compression modulus of the mechanical test results were recorded at 40 kPa. These results are promising to indicate that bamboo fibre has potential as a viable substrate for MBCs. (Tseng et al., 2024)

Bamboo must be used as a stiff-macro reinforcement scaffold. Bamboo is a highly accessible, traditional construction material. It is celebrated globally for its exceptional strength-to-weight ratio. Uncompressed mycelium inherently acts as a brittle, foam-like binder, the composite requires the integration of long, continuous fibres to resist fracture under load (Voutetaki & Mpalaskas, 2024). By utilising rigid bamboo strips as an internal scaffold, the material benefits from an internal skeleton that can effectively distribute multidirectional stresses while the mycelium acts as the

stabilising, compressive matrix.

### 8.2 Weaving patterns

Traditional weaving patterns were explored as a method for developing reinforcement scaffolds. The geometry of the different types of woven base like square, circular and polygnal (Fig. 22) further informed the importance of load-transfer paths and weaving trajectories. The selection therefore influenced the porosity and structural behaviour of the scaffold system.

A study by Hebbar (2015) further informs the dimensions and orientation of the bamboo strips affecting the stiffness and porosity of the woven framework. (Fig. 24) Wider and thicker strips (8mm wide and 1.5mm thick) created more rigid geometries with larger cellular openings. In contrast, thinner strips (3mm wide and 1.5mm thick) generated denser and more intricate weave patterns.

To counteract the flexibility of the natural fibres and reinforce the geometry, the application of “twisting” is highly important. This creates concentrated zones of rigidity when joining two or more surfaces together. This would help in fabricating the scaffold rigidly (Hebbar, 2015).

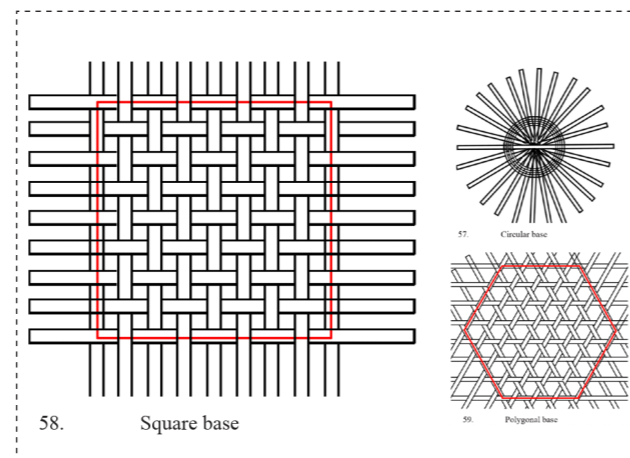


Figure 22: Types of bamboo woven bases (Source: Hebbar, 2015)

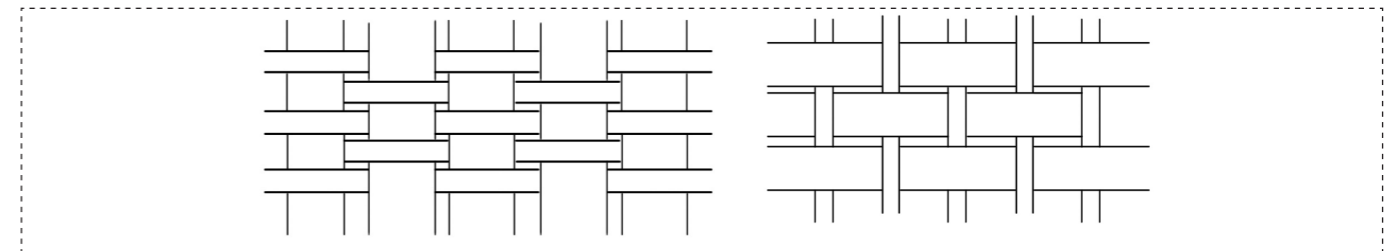


Figure 23: Thickness variations; (left) Warps wider than wefts; (right) wefts wider than warps (Source: Hebbar, 2015)



Figure 24: (top) Basket weave pattern 8mm wide, 2mm thick; (bottom) Weave pattern 3mm wide, 1.5mm thick (Source: Hebbar, 2015)

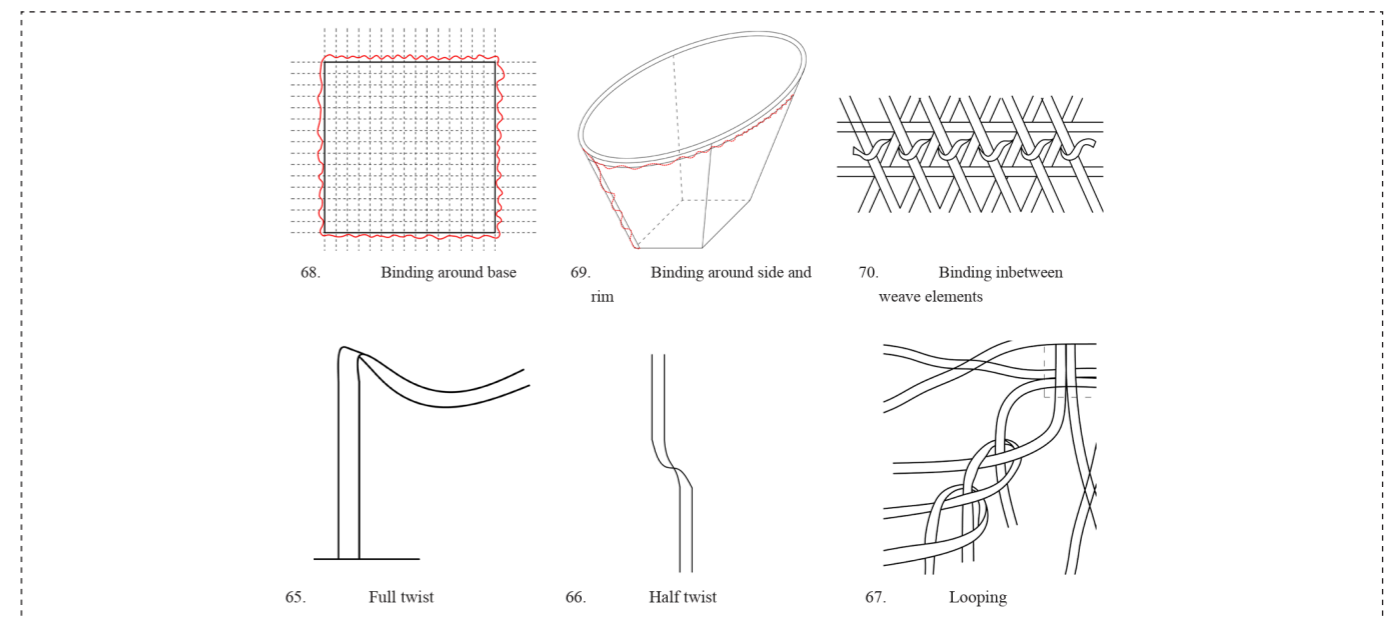


Figure 25: (left) Twisting for strengthening; (right) Locations of twisting (Source: Hebbar, 2015)

### 8.3 Limitations

The primary limitations are the inconsistency of its natural growth and presence of anatomical nodes (knots) at random intervals along the culm. Natural variations like fluctuating wall thickness, tapering diameters make it difficult to extract uniform and standardised strips. This makes the material harder to manipulate, increasing the risk of micro-cracking or structural failure when tightly weaving complex patterns (Tseng et al., 2024).

To mitigate these natural inconsistencies and standardise the material for architectural use, research within the domestic bamboo industry has proposed a series of renovation strategies aimed at reassessing bamboo development. These strategies address stable bamboo sourcing, product processing technologies and reuse of residual materials with the objective of re-evaluating bamboo's versatility. (Tseng et al., 2024).

### 8.4 PART A: Conclusions

- Mycelium functions as an active biological binder that inherently provides secondary material benefits, including acoustic attenuation, thermal insulation, and complete biodegradability.
- Selecting an appropriate lignocellulosic substrate is critical to maximising the interfacial bonding strength of the composite matrix.
- Integrating a scaffold significantly improves mechanical capacity, as the hyphal network actively colonizes and binds to the directional framework.
- The initial packing density and macroporosity of the substrate directly dictate mycelial proliferation by governing internal oxygen diffusion.
- Woven bamboo serves as an optimal scaffold; its structural stiffness ensures geometric stability while allowing for precise control over the matrix's structural density.

# MATERIAL EXPERIMENTATION

Part B



# 9.0

## Material exploration: Bamboo Reinforced MBC

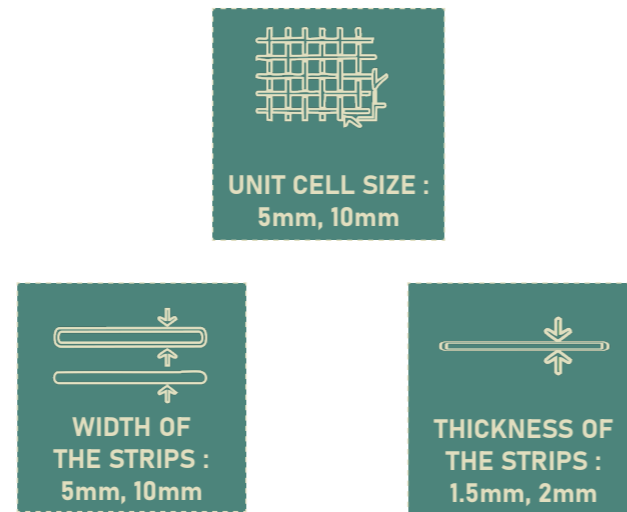


Figure 26: Resulting Variables (Author)

forms bonds with secondary substrates around the woven bamboo forms.

- to control and enhance the growth of mycelium with different variations of bamboo strips owing to origin, thickness and widths.

Although the objectives were clearly set at the beginning of the research, they were intentionally kept broad in some areas **to allow the material behaviour and experimental observations to inform the direction of the study over time**. Due to large number of variables involved and the absence of a standardised procedure for producing MBCs, it became important to limit and carefully define the primary variables. This was only possible after keeping the remaining aspects of the fabrication

The theoretical framework established in the Part A literature review directly informed the subsequent material experimentation phase. Specifically, these preliminary findings guided the selection of an optimal lignocellulosic substrate and justified the integration of woven bamboo as a necessary structural scaffold to enhance the mechanical capacity of the Mycelium-Based Composite (MBC).

### 9.1 Objectives

The main objectives of this material research were:

- to investigate how mycelium grows and

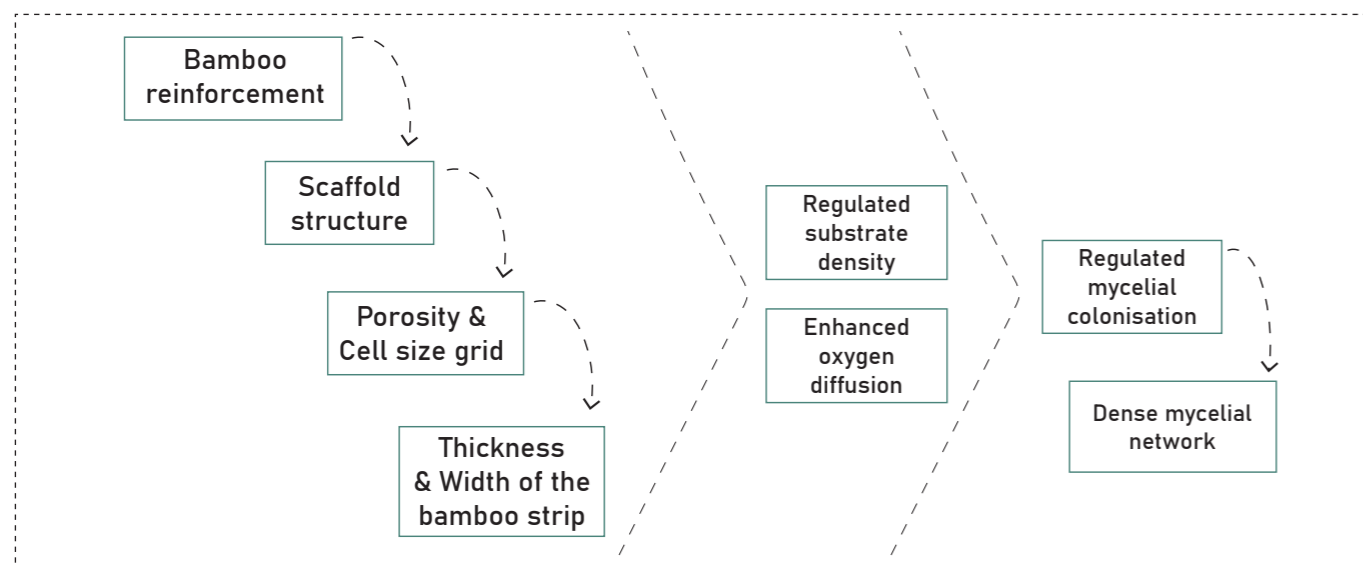


Figure 27: Variables' dependency flow on the scaffold structure type (Author)

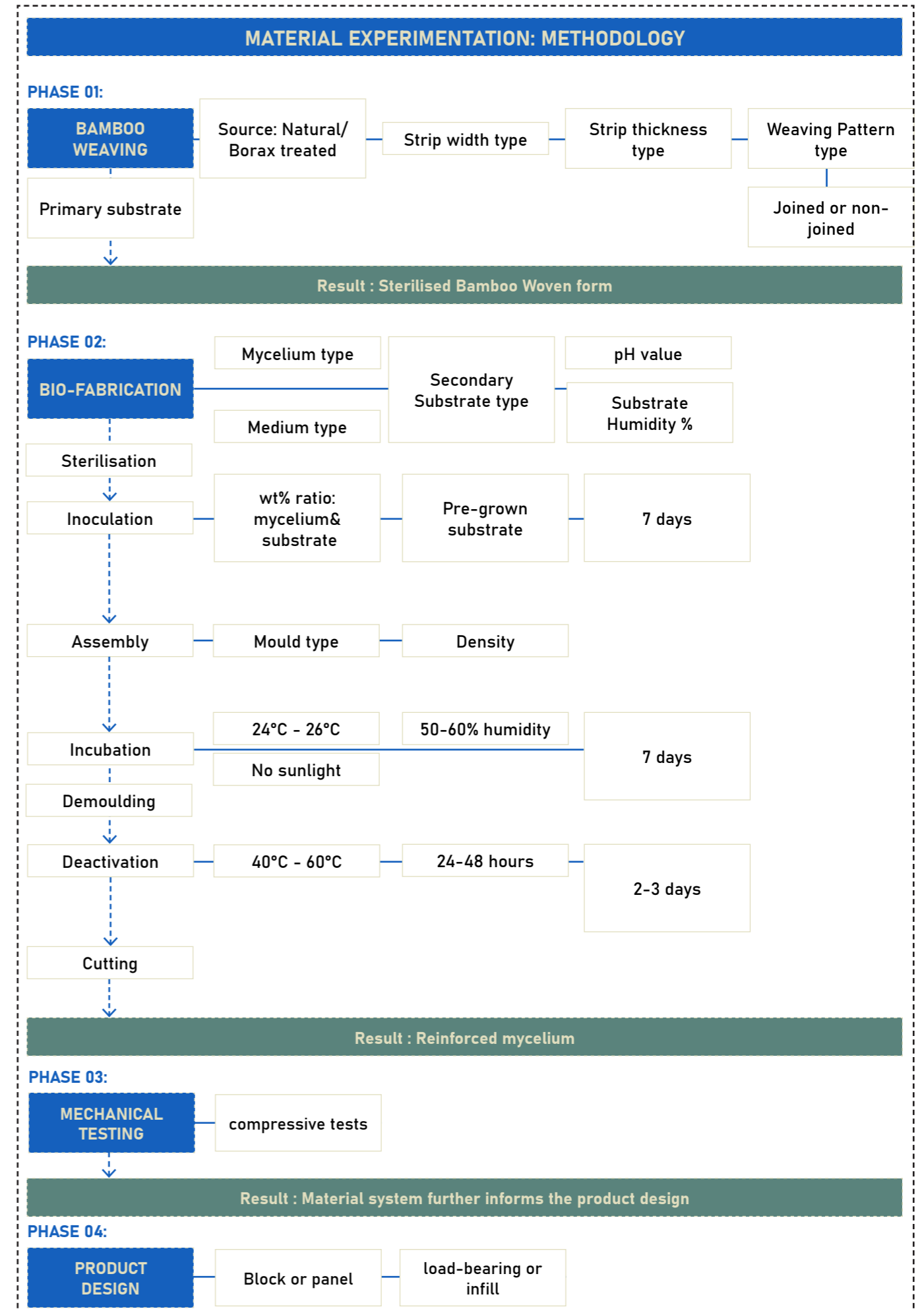


Figure 28: Material Experimentation: Methodology (Author)

process consistent. This approach enabled the development of a more controlled and closely related set of experiments, resulting in data that could be compared more reliably across different iterations and stages.

The three primary variables established were (Fig. 27) **unit cell size, thickness of the strip and width of the bamboo strip**. These variables were selected based on their expected influence on the substrate distribution, airflow, structural behaviour and mycelial colonisation within the composite system. At the same time, it was understood that developing a stable mycelium growth protocol would involve a degree of variability and trial-and-error experimentation before arriving at a finalised fabrication recipe.

While the research conducted by Sharma et al. (2025) concluded with 50% porosity (Section 6.1) as the most favourable conditions, it was important to determine the appropriate porosity range for this substrate and reinforcement composition used in this research. This directly informed the development of different unit cell sizes within the woven bamboo, which further translated into variations in bamboo strip thicknesses and widths. As the experimental stages progressed, a deeper understanding of the material behaviour was realised. This refined the scope of the research



Figure 29: Particle size of each substrate (Author)

gradually to further focus on more feasible, controlled and relevant objectives. (Sharma et al. 2025).

### Material prototype description:

The material prototype maintained a constant thickness range of 50mm throughout the experiments. In discussion and consultation with Tjeerd, the thickness range was selected as a balance between structural depth, material handling and the ability to support effective mycelial colonisation for consistent oxygen diffusion.

Previous research concluded have thinner MBC panels offer significant advantages due to their higher surface to thickness ratio thus improving aeration and oxygen circulation. Based on this principle the *Mycoply* system developed thicker building component by laminating multiple MBC sheets with the process of bio-welding of the outer mycelial skins. Thicknesses of 24mm, 48mm and 72mm were produced as assemblies (Wisniewska et al., 2025).

### Target compressive strength $\geq 7.29$ MPa:

Previous research has shown that MBCs demonstrated their potential for low load-bearing applications. Earlier studies reported yield strength ( $\sigma_y$ ) values for MBCs ranging between 0.1 MPa and 0.7MPa. In comparison, the fabrication method developed by Sharma et al. (2025) achieved significantly higher yield strengths, 7.29 MPa being the maximum. This study concluded the presence of the scaffold system helped improve the structural growth of mycelium from 9.5% to 77.77%, thus resulting with improved mechanical performance (Sharma et al. 2025).

Based on these findings, a target compressive strength of at least 7.29MPa was established within this research as a reference benchmark for evaluating the structural performance and reinforcement potential of the composite system (Sharma et al. 2025).

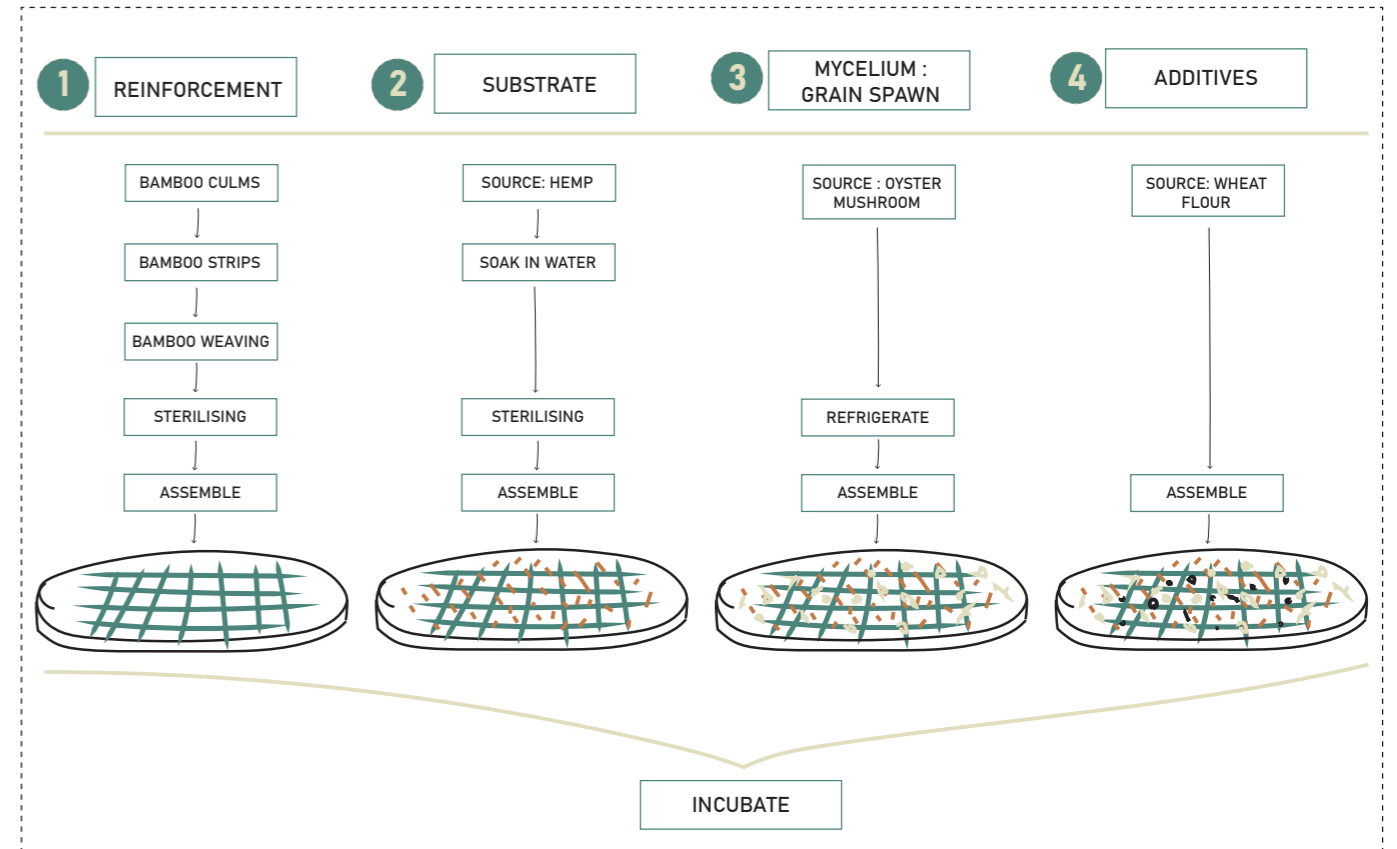


Figure 30: Assembly; Recipe components of the process (Author)

## 9.2 Methodology

### 9.2.1. Phase 01

Sourcing natural bamboo that had not been treated with borax (Section 10.1.1) was an important starting point. As a standard industry practice, bamboo is commonly soaked or sprayed with borax after harvesting to prevent fungal growth. Given the objectives of this research, untreated bamboo was preferred for an efficient mycelial colonisation.

With basic prior experience of working with bamboo culms, working with bamboo strips and weaving was entirely a new domain that required learning and exploration through hands-on experimentation. The early stages focused on understanding the material behaviour, flexibility and limitations of bamboo weaving.

The overall intention was to develop a simple weaving system that could be replicated consistently across multiple specimens. Many weaving forms were explored but several attempts proved difficult to control

or reproduce consistently. Eventually, moving towards a more straightforward weaving pattern that was easier to replicate consistently.

### 9.2.2. Phase 02

Biofabrication with Mycelium was a trial and error process due to the large number of variables that needed to be controlled throughout the process. Establishing a stable and repeatable protocol therefore became essential to develop relatively low-energy fabrication process capable of producing reliable results.

The process followed the standard steps of inoculation, assembly, incubation and deactivation. The behaviour of mycelium as a living and growing material meant that small variations in substrate preparation, moisture content or airflow resulted in noticeably different outcomes between specimens.

The strategy was guided by the objective of improving compressive strength. Therefore,

material choices, weaving pattern, substrate preparation and growing conditions were gradually adjusted to their influence on the structural integrity of the composite system.

### 9.2.3. Phase 03

Once the MBC was ready, it was subjected to mechanical testing. The goal was to test the material for load-bearing compressive strength. Having a pre-set limitation of 50mm as the maximum width for growing mycelium, the material was explored for a block or a panel. This would eventually inform the Phase 04 for the use of the material system into a product form and architectural applications.

## 9.3 Recipe components

### 9.3.1. Primary reinforcement: Bamboo

This acted as the base structure, in this case acting as the reinforcement of the material system. As the primary substrate, it was critical for bamboo to support mycelial growth effectively, allowing it to grow through and around the weave thus creating a dense binding matrix. Any chemically treated bamboo was considered unsuitable, as the borax treatment residues could hamper the mycelial growth.

It was crucial for the bamboo strips to maintain consistent thickness and widths so that the experimental results could remain controlled and comparable across iterations. Excessive irregularities would not provide a scientific conclusion from the experiments. Maintaining this consistency also allowed greater control in modifying the unit cell size of the woven bamboo.

### 9.3.2. Secondary substrate

The selected substrate was required to satisfy several performance criteria. Primarily, it needed to contribute to the compressive strength while maintaining a sufficiently short fibre morphology to effectively act as an infill around the bamboo

reinforcement.

The substrate also needed to retain adequate moisture to support consistent mycelial colonisation, while preserving sufficient porosity to facilitate oxygen penetration throughout the substrate. Achieving this balance was critical to ensure uniform fungal growth and consistent material quality. In conclusion to the performance criterias, Hemp, straw and saw dust were the 3 choices to further evaluate how each of the material would react and respond to the growth to further narrow down to one of them.

**Hemp** (short fibers) was selected for its high tensile stiffness, proven mechanical and acoustic performance and sustainability benefits through agricultural waste utilization. It was incorporated at 15% (H1); 30% (H2); 60% (H3) of primary substrate weight (Amundhan et al., 2025).

As identified in previous research, hemp has been one of the most widely used substrates in construction based projects. These case studies include the *Hy-Fi Pavillion*, *El Monolito Micelio*, *the Growing Pavillion*, *Mycomerge*, *The Phoenix Affordable housing project* (Refer Section 5).

Similarly, **Straw** is also one of the other materials that has also been widely used as an alternative for its popularity of being highly compatible and favourably high in mechanical characteristics. In the research findings, straw (long fibers) was selected for higher flexural strength compared to many natural fibers, local availability. It was incorporated at 15% (S1); 30% (S2); 60% (S3) of primary substrate weight. Straw enhances flexibility and dimensional stability at low percentages (Amundhan et al., 2025). The test also had a combined formulation (SH) 15% straw + 15% hemp to evaluate synergistic effects on material properties (Amundhan et al., 2025).

In addition, several studies (Section 3.2) have identified **saw dust** being quite a good

alternative due to its fine particle size which improves the filler distribution. Each of these materials was shortlisted from a broader range of tested substrates and their individual capabilities to finally be able to arrive at one.

### 9.3.3. Mycelium type

**Liquid culture** is a sterile liquid solution containing actively growing mycelium in a medium that is rich with nutrients like malt extract or honey, commonly prepared using water. It is more concentrated than other mediums which allows the mycelium to spread rapidly through the substrate resulting in faster colonisation. Alternatively, it is also more vulnerable to contamination if sterile conditions are not carefully maintained throughout handling and inoculation.

**Grain spawn** is a carrier material used to grow mycelium, it typically consists of sterilised cereal grains such as oats, millet, wheat or rye that have been inoculated with fungal culture. The grain provides nutrients which in turn supports rapid mycelial colonisation. This is also one of the most common methods followed by multiple researchers. Contamination is very easy to spot, widely commercially available and relatively easy to ship. This makes it very accessible and widely adopted inoculation system.

### 9.3.4. Additives

As per the literature (Section 6.1), Peptone-Malt-Agar (PMA) coatings influenced mycelial growth depending on concentration. At 2–5 wt%, the mycelium formed a fluffy, highly porous layer while at 20 wt%, growth produced a dense structure with slower expansion. At 10 wt% resulted in healthy, vigorous, and uniform growth across the scaffold. (Sharma et al., 2025) Another study suggests, Wheat flour boosts strength and growth rate and guar gum improves skin quality and shrinkage control (Amundhan et al., 2025).

Based on these findings, it was critical to understand how different additives and their quantities could influence the quality of mycelial growth. Due to the limited research available on mycelial colonisation around woven bamboo strips, careful selection of additives was necessary to maintain optimal interaction between bamboo reinforcement and growing mycelium matrix.

# 10.0

## Preparation

### 10.1 Sourcing

#### 10.1.1. Bamboo (Primary substrate)

As mentioned earlier, sourcing natural bamboo that had not been treated with borax was an important requirement. Bamboo strips purchased from online suppliers are typically processes, packaged and chemically treated with borax to comply with European import and preservation standards. Such treatments were unsuitable for the material research.

Several companies actively working with bamboo in the Netherlands were therefore contacted. Brian from the Dutch Bamboo foundation recommended some companies like Studio Akeka, Bamboo logic, Mycelco,

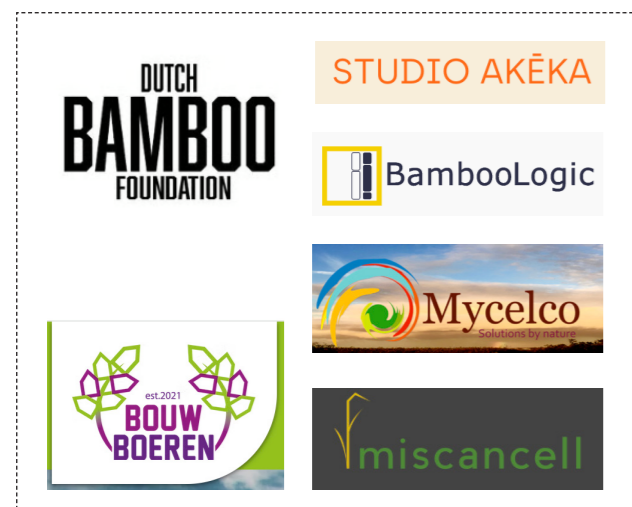


Figure 31: Companies working with Bamboo in NL (Author)

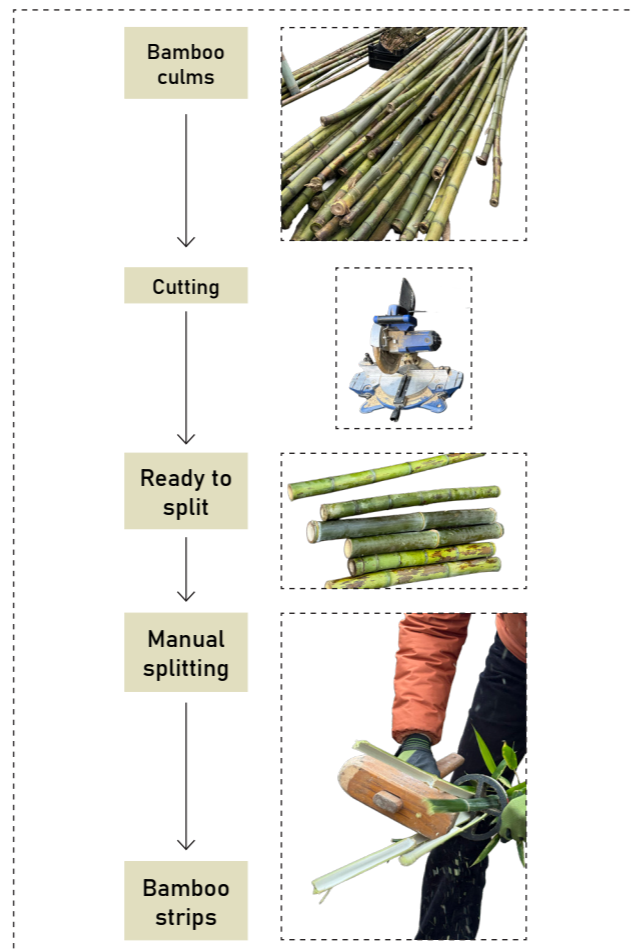


Figure 32: Production process of bamboo strips from bamboo culms (Author)

Bouw Boeren and Miscancell. However, these organisations primarily worked with bamboo in other forms and did not produce bamboo strips as a standard material product.

Hans from De Groenprins kindly invited me to his bamboo nursery in Steenwijk to explore the process of manually splitting natural bamboo culms into strips from his available stock. We later visited the studio of artist Karen van der Molen, who works extensively with bamboo. She demonstrated a rudimentary method for splitting bamboo into thinner sections suitable for weaving.

One sample was produced through this process, however it quickly became evident that the method would not provide bamboo strips suitable for controlled hand weaving and repeatable experimentation. Manual longitudinal splitting resulted in reinforcement strips characterised by inconsistent cross-sectional dimensions. These specimens were inherently prone



Figure 33: Sourcing map (Author)

to structural irregularities, warping, and uncontrolled splitting along the fiber axis. Such variations would make it difficult to maintain controlled experimental conditions and would not support scientifically reliable results across multiple iterations.

**This became an important realisation within the research, highlighting how difficult it was to source naturally processed and untreated bamboo strips suitable for controlled experimental use.**

This challenge eventually led to the search for alternative sourcing options online and outside the Netherlands. Since I had previous experience working with craftspeople in Mumbai, India, I reached out to them for guidance and support regarding natural bamboo strips for weaving. Online platforms such as Amazon and Temu offered several readily available bamboo strip options. However, all of these strips would likely be treated with borax and would take a minimum delivery time of two weeks.



Figure 34: Liquid Culture from STV(top) and Grain Spawn(bottom) from Rotterzwam (Author)

To continue the search for natural untreated bamboo, sourcing possibilities in India were also explored. After contacting several local suppliers, it became evident that rattan strips were more commonly available than bamboo weaving strips. Eventually, a supplier named Daisy life based in Pune agreed to ship bamboo strips within two days and would take two weeks to be delivered. These strips were hand cut and naturally processed, therefore not fully identical in size and geometry due to absence of machine processing.

**Types of bamboo finally ordered were :**

**From Temu (China):**

- Small - 5mm (w), 0.5mm (t)
- Medium - 8mm (w), 0.5mm (t)
- Large - 10mm (w), 0.5mm (t)

**From Daisy life (India):**

- Small - 5mm (w), 0.5mm (t)
- Large - 10mm (w), 0.5mm (t)



Figure 35: Hemp (left) and Straw (right) from Ranzijn Tuin & Dier (Author)



Figure 36: Equipments for the experiment (Author)

**10.1.2. Mycelium**

The primary biological binder utilised for this study was a Yellow Reishi (*Ganoderma lucidum*) fungal strain. The foundational biological material was propagated from a liquid culture, dated 16/09/2025, which was generously provided by Studio Tjeerd Veenhoven (STV).

Oyster mushroom (*Pleurotus ostreatus*) grain spawn was sourced directly from Rotterzwam (Rotterdam, NL). Preliminary consultations with their specialists underscored the critical influence of weight percentages (wt%), additive ratios, and pH levels on successful mycelial proliferation.

**10.1.3. Secondary substrate**

Hemp shives and straw were procured from Ranzijn tuin & dier, Delft. Saw dust was collected from residual waste generated within the wood workshop at STV.

**10.1.4. Equipments**

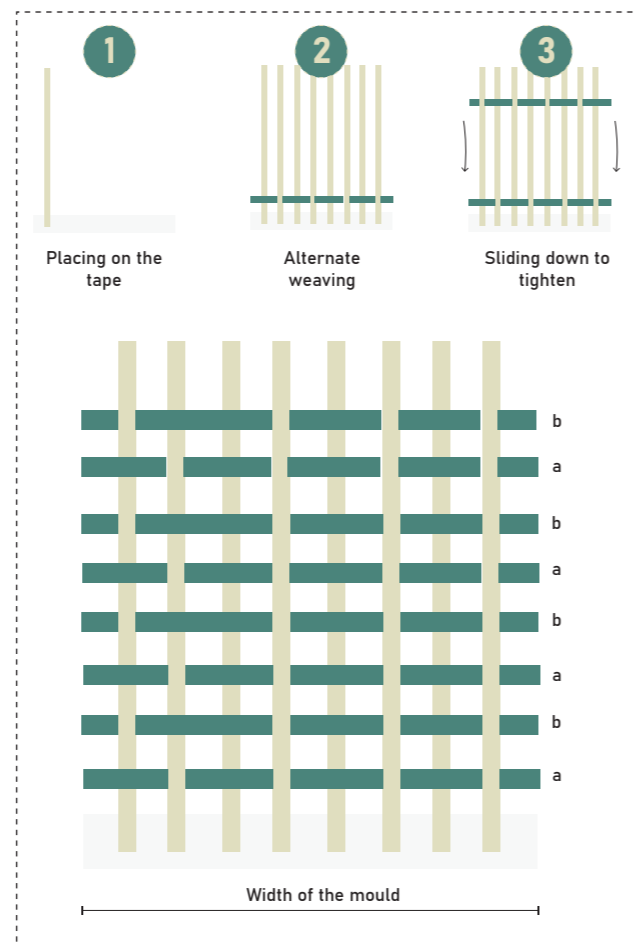


Figure 37: Bamboo Strip Weaving (Author)

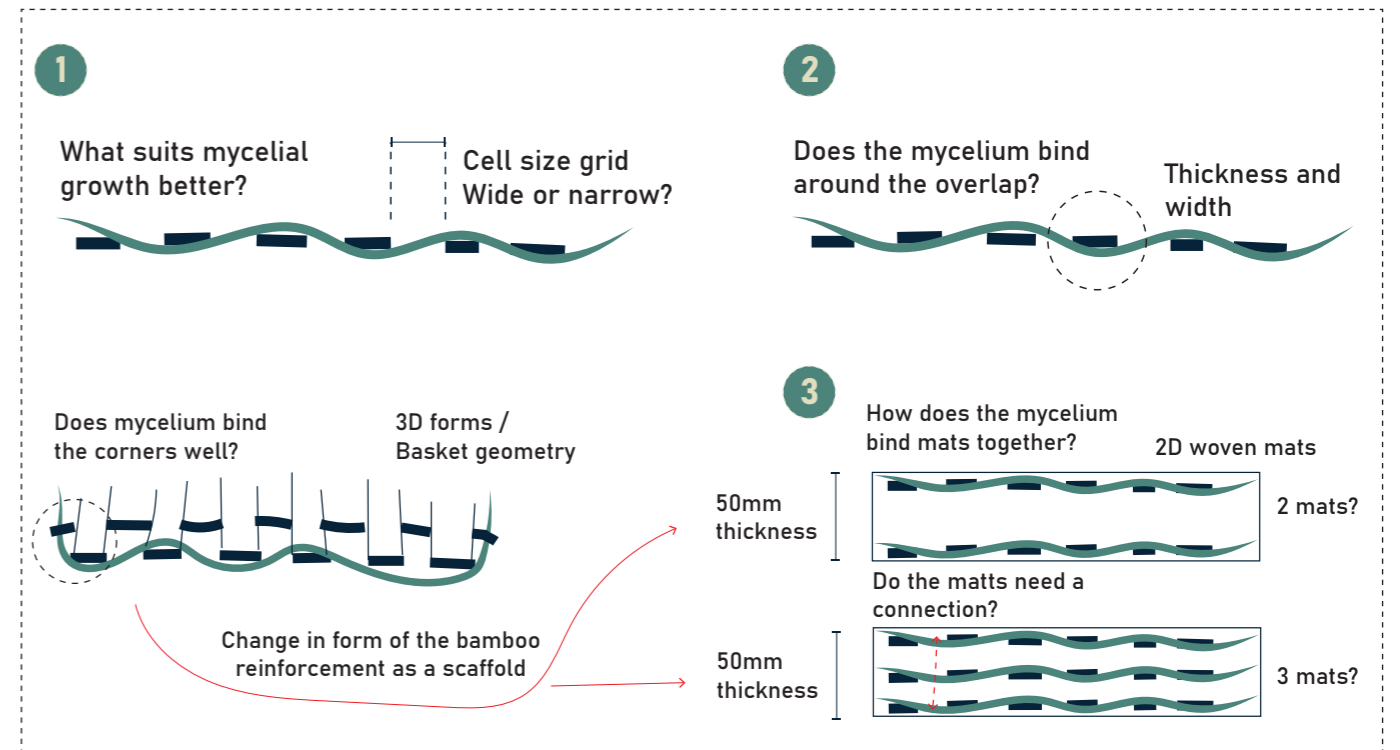


Figure 38: Modifying methodology after first round of bamboo weaving (Author)

To maintain sterile working conditions throughout the experimental process, isopropyl was procured from Herrlan-Shop NL. Hygrometer was procured from Ranzijn tuin & dier. Gloves, duct tape and household thermometer were procured from Temu. Weighing scale was procured from Ikea. Plastic wrap and aluminium foil was procured from Jumbo. All the other equipments like bowls, spoons, sieve, scotch tape, scissors, tweezers, cutter, tissue consisted of standard household items already available.

**10.2 Bamboo weaving**

**10.2.1. Early weaving**

Following a two week delivery period, initial material explorations were conducted with the bamboo strips. These included triaxial weaving patterns, grid-based weaving and preliminary attempts to create basket-like forms and three-dimensional forms. Consultations were also conducted with the bamboo specialist team at Tiny Cane Collective in India through Ritika to gain instinctive insights of the craftspeople there. It was learnt that soaking bamboo in

water made the material more flexible and easier to weave. It was also understood that weaving practices in India commonly use natural untreated bamboo, which is later treated with borax to improve durability. These explorations aimed to understand the material's feasibility to weave for forming a reinforcement within the composite system.

**10.2.2. Modifying methodology**

Some observations from the weaving explorations informed further development of the composite system. During fabrication, weaving patterns involving two directional axes were found to be relatively controllable and stable. The introduction of a third directional axis, made the weaving process more difficult to manage consistently. Being a beginner myself, it was difficult to achieve accuracy. Additional experiments were explored for basket-like geometries using a grid-weave base. While the flat woven base could be achieved relatively easily, difficulties increased when the weave needed to be tightened to create vertical surfaces and enclosed forms. At this stage, maintaining the tension, alignment and control over the bamboo strips was very weak limiting the precision of the woven

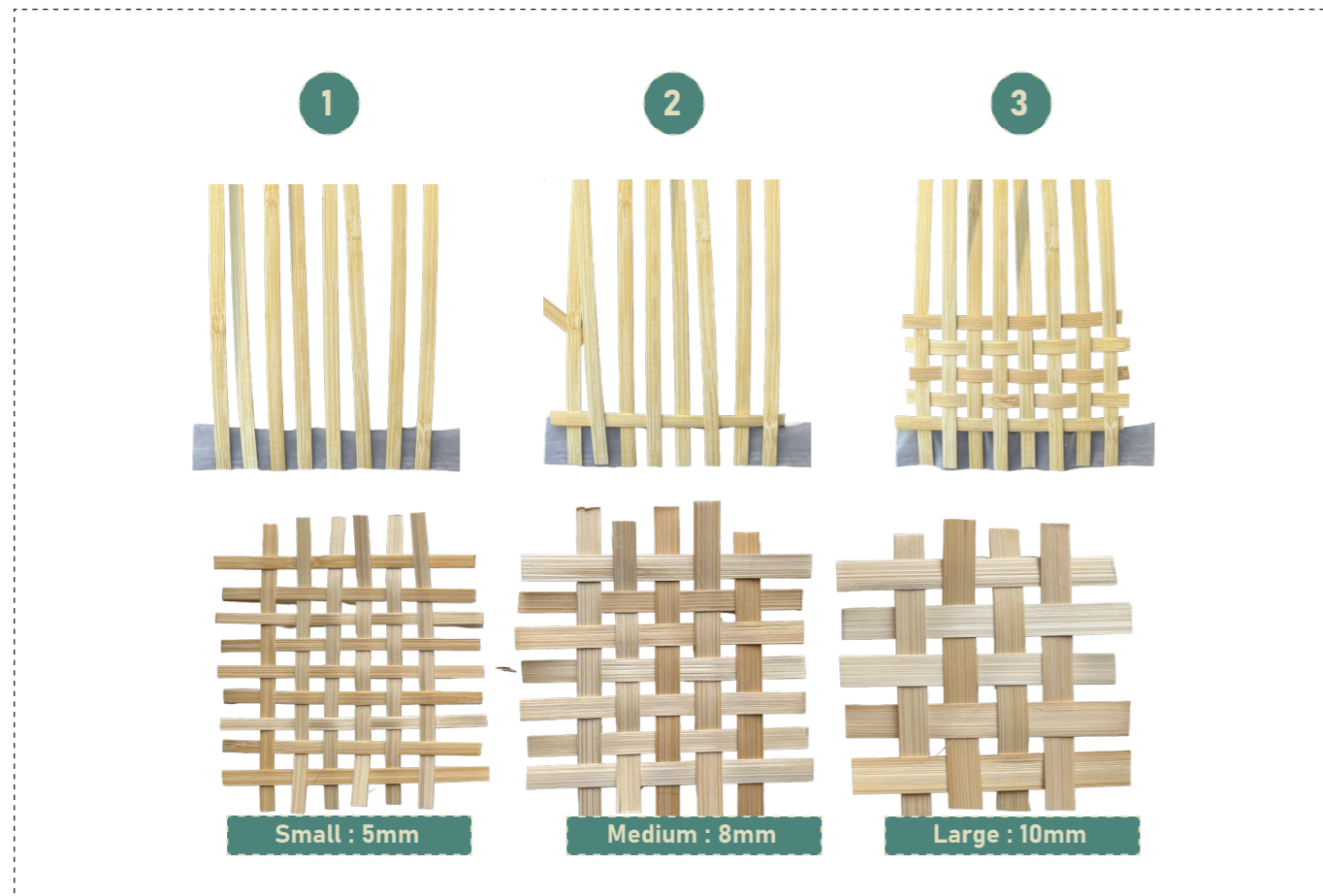


Figure 39: Bamboo weaving: Origin Type 01, China (Author)

form.

To maintain better control over the material behaviour, a decision was made to continue working with two flat WBM's integrated as layers within the composite system.

### 10.2.3. Grid-pattern weaving; Origin Type 01

All the early weaving experiments were conducted using Origin Type 01 bamboo strips, which were sourced from China through Temu. During the weaving process, the grid cell size was highly governed by the strip thickness and the extent to which the strip allows to be closer together. This directly affected the density of the weave, resulting in tighter and stiffer woven configurations.

To start with, tape is required to keep the longer bamboo strips in place to maintain alignment (Fig. 40). Shorter strips were then woven alternately through the longer strips to create the grid pattern. Once the three shorter strips were interlocked into

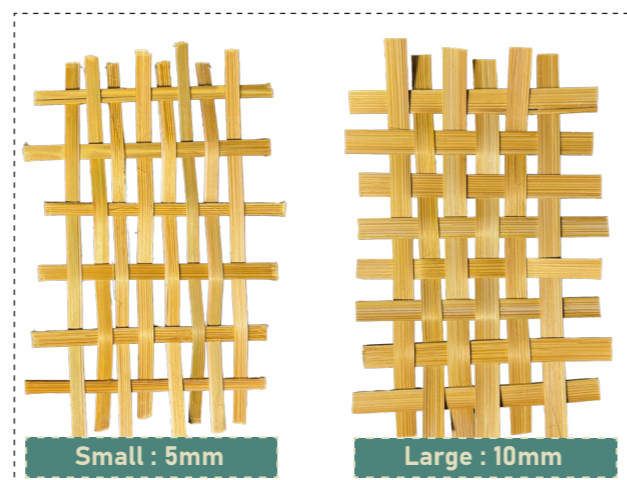


Figure 40: Bamboo Origin Type 02, from India (Author)

the grid format, it starts to take shape and the system began to stabilise. Throughout the process, it was important to allow the material to govern the tightness between adjacent strips, rather than forcing the weave beyond its natural flexibility.

Any cracks or splits observed within the strips were avoided or cut off to maintain the integrity of the woven structure. Additionally, it was observed that the wider the strips the more easier they were to weave, but at the

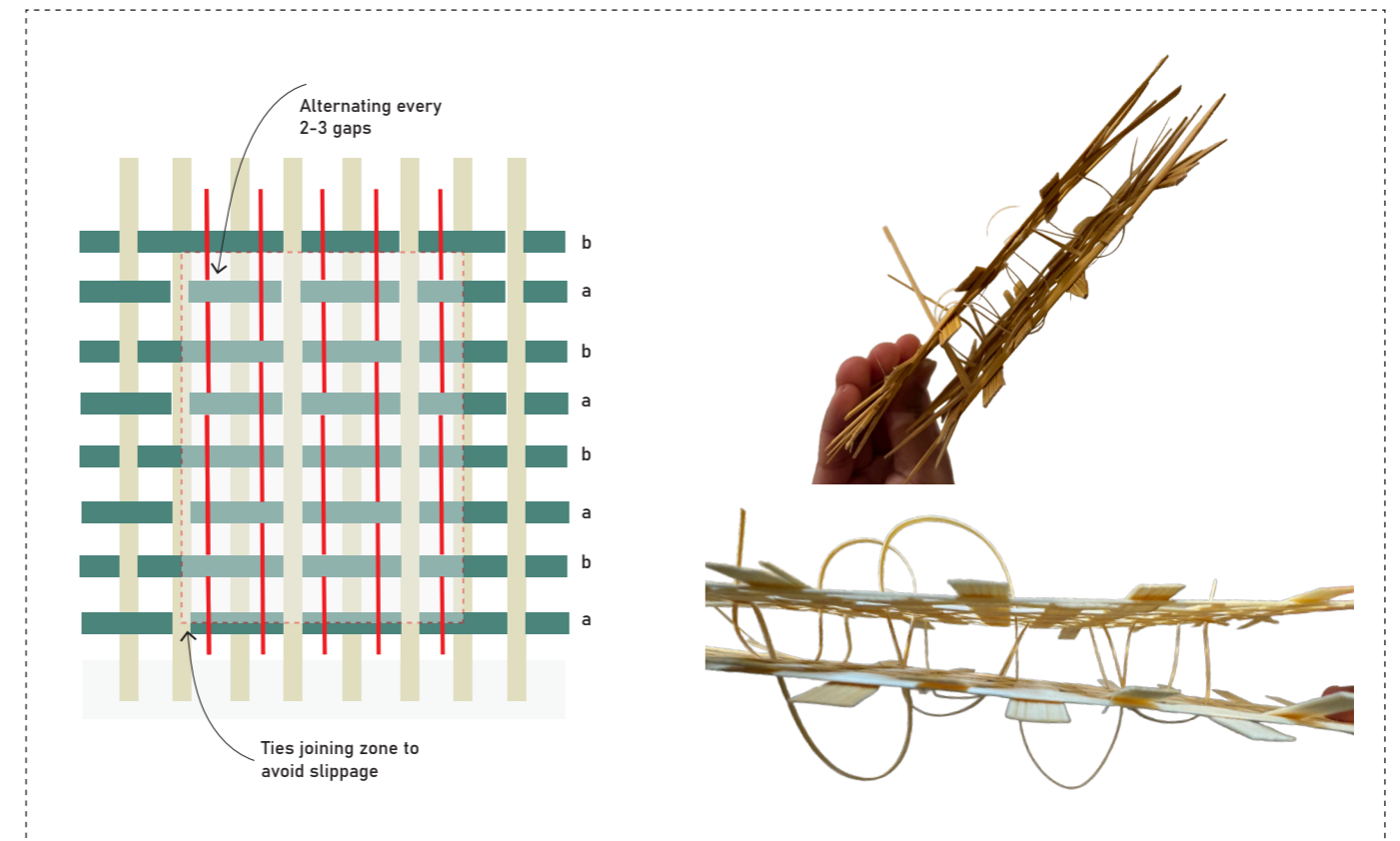


Figure 41: Joining 2 WBM's with ties (Author)

same time, they were more prone to splitting and cracking along the centre of the strip.

### 10.2.4. Grid-pattern weaving; Origin Type 02

While working with the strips sourced from China, a second batch of bamboo strips from India (Origin Type 02) arrived after approximately three weeks. The strips were required soaking in water for at least two hours to improve flexibility and workability. The strips became softer and slightly easier to bend. The strips still remained considerably stiff and difficult to handle during the initial times of weaving.

In comparison to Origin Type 01, these strips had slight irregularities in thickness and width, and their natural curvature created additional difficulties during weaving. Maintaining the alignment of the longer strips while weaving the shorter strips was particularly difficult as the strips would frequently slip out of position due to their slightly curved surfaces. After four to five attempts, it became relatively easier and familiarity with the material improved. It was also observed that using an odd

number of longer strips improved stability during weaving and would not slip off easily.

Overall, Origin type 02 bamboo showed significantly more stiffness, durability and robustness compared to Origin type 01.

### 10.2.4. Ties

In the later stages, bamboo ties were introduced to join the woven mats together. These ties functioned similarly to stirrups in steel reinforcements, helping maintain spacing and improving stability of connection with the mats together. The ties needed to be thin enough to allow tightening without splitting at the centre, while also being able to maintain tension along their length.

Many of the ties snapped in the early trials when woven through alternating gaps between the strips. To improve stability and reduce breakage, the ties were eventually woven by leaving at least two gaps between each connection. Eventually, it was also important that those ties remain at least two strips away from the corners of the woven mats, as ties placed too close to the

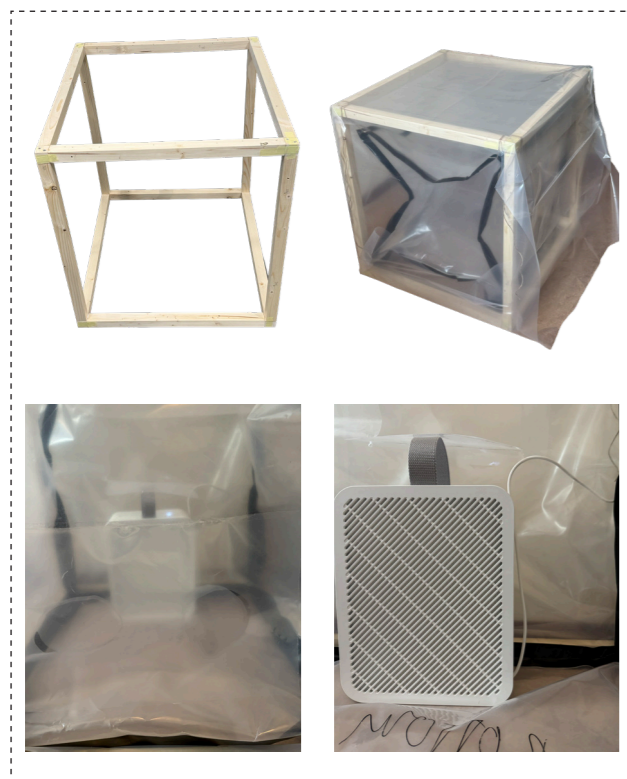


Figure 42: Clean Box (Author)

edge caused the grid weave to loosen and pull out more easily.

### 10.3 Domestic protocol

Before starting with the main experiment, it was important to understand and understand the basic protocol of growing mycelium at home. This experiment only involved hemp as the substrate. Since the experiments were to be conducted at Studio Tjeerd Veenhoven in Groningen, prior hands-on experience became necessary as the visits to the studio were relatively limited due to the travel distance.

#### 10.3.1. Setup: Clean room/box

A clean room or clean box was developed as a portable sterile setup to minimise any airborne contamination during mycelium handling and assembly processes. A timber frame measuring 70cmx70cmx70cm was constructed at the wood workshop within the Faculty of Architecture & the Built Environment (Bouwkunde) using redundant waste wood. With the assistance from Tjeerd's team, a high-grade plastic lining cut out for the setup. It was later installed within the frame to create an enclosed



Figure 43: Hemp preparation & autoclave (Author)

working chamber. To improve air quality while working, a filter unit from from Ikea UPPÅTVIND was incorporated in the setup. Access openings for hand movement were also cut into the enclosure to allow sterile handling during inoculation and assembly procedures.

#### 10.3.2. Borax removal of Bamboo

As mentioned earlier, packaged and processed bamboo from Origin Type 01 was likely to contain traces of borax treatment. Therefore, the WBM's were boiled in water for approximately two hours, with the water replaced once during the process to help remove any residual treatment chemicals. The mats were then wrapped in aluminium foil before undergoing the autoclave sterilisation process.

#### 10.3.3. Pressure cooker sterilisation

Hemp shives were prepared for sterilisation by soaking them in water at approximately 80-90°C for 2 hours to improve water absorption and moisture retention.

The soaked substrate was then transferred into autoclave bags and compressed as



Figure 44: Domestic protocol: Inoculation and growth progress (Author)

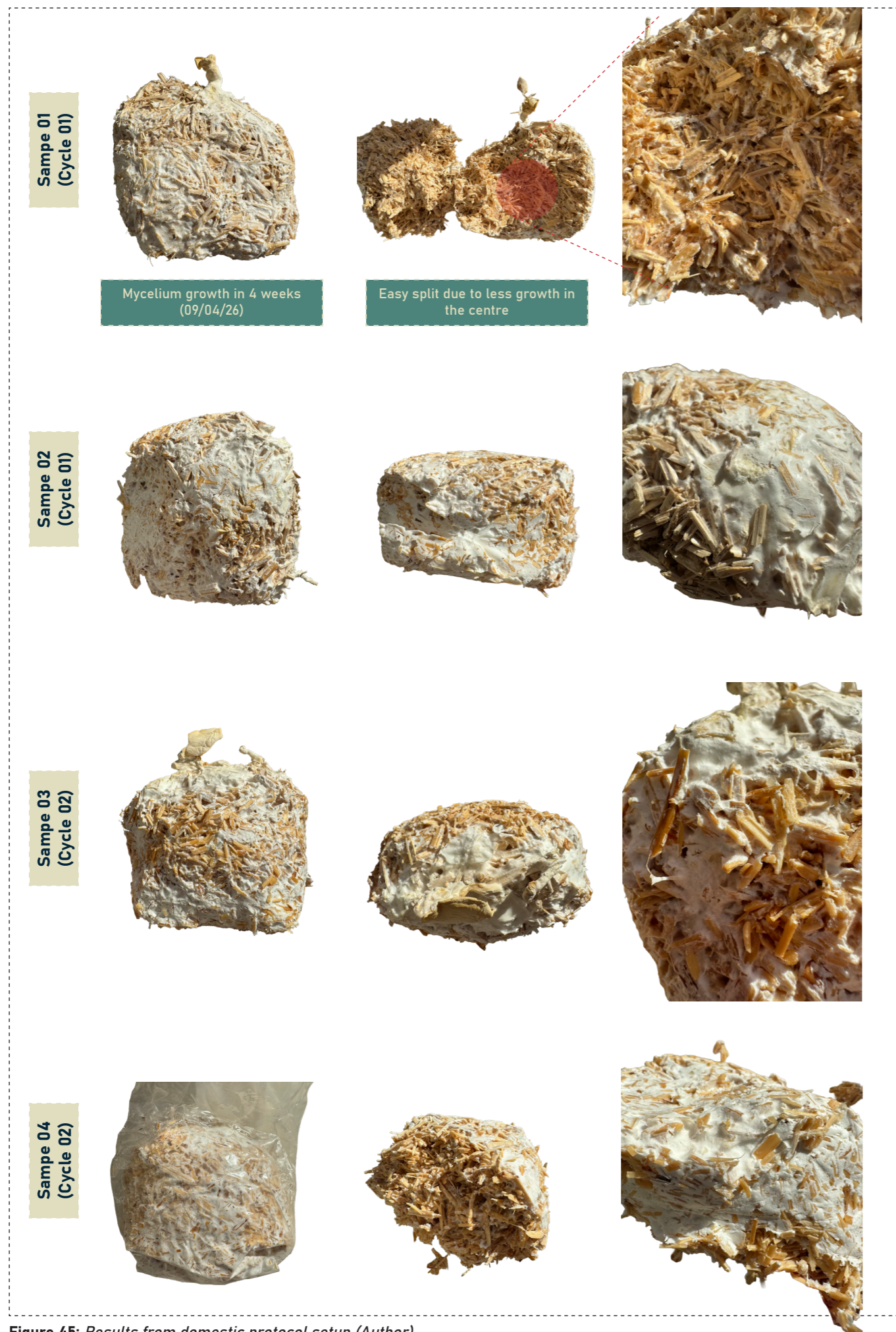


Figure 45: Results from domestic protocol setup (Author)

much as possible to remove excess air. Smaller bag sizes were maintained to ensure they could fit properly inside the 2.5L Stahl pressure cooker and sit flush during sterilisation. A raised platform was placed inside the cooker to prevent direct contact between the bags and bottom surface. It was also important to keep the bag opening tucked below and away from the steam valves to allow free steam circulation throughout the sterilisation process.

Initially, the pressure weight was removed to allow steam to escape continuously for 15 minutes. The cooker was then operated at the maximum capacity, that being approximately 15 psi (~ 1 bar) for 15 mins under maximum heat at the induction. Another 15 minutes under level 4 heat before allowing to cool down for another 15 minutes. After the process was completed, the substrate was allowed to cool down completely before inoculation.

The same sterilisation process was also carried out for WBMs which were wrapped in aluminium foil prior to placement inside the pressure cooker.

#### 10.3.4. Inoculation

Inoculation was carried out inside the clean box to maintain sterile working conditions. All surfaces were sterilised using isopropyl alcohol and gloves were worn throughout the process to minimise contamination. Oyster mushroom grain spawn was used at 15 wt% and mixed thoroughly with the secondary substrate to ensure even distribution of the mycelium. The grain spawn was stored in the refrigerator for approximately 20 days to preserve its viability before it was used for inoculation.

#### 10.4 Variables selection matrix

Following the preliminary material explorations and the identification of key factors governing the composite system, it became imperative to establish a rigorous set of experimental variables for the formal

laboratory protocols. This stage became an important filtering step, helping narrow down many of the variables that were originally planned for testing. As a result, it became possible to define a clearer set of experimental variables for the laboratory protocols.

Establishing these variables allowed for systematic testing and comparison of different material combinations to evaluate whether WBMs used as reinforcement contributed meaningfully to the structural performance. The remaining variables related to mycelial growth were primarily optimised to achieve healthy colonisation.

To start with, two mycelium inoculation methods were selected: liquid culture and grain spawn each with a different type of strain. Two weaving patterns for the bamboo mats, grid weave and triaxial weave. Each of them produced using three strip widths: small (5mm), medium (8mm), and large (10mm). The depth of the material composite system was at a constant of 50mm while the number of woven mats placed within it varied between two, three and four layers. Finally, three secondary substrates were part of the matrix being hemp, straw and saw dust. In conclusion, it was a good starting point to start with the Stage 00 protocol which would eventually inform the development of subsequent experimental stages.

#### 10.5 Key takeaways

- Utilisation of two-dimensional woven bamboo mats as the primary structural reinforcement.
- Comparative structural analysis of unreinforced composites versus bamboo-reinforced composite assemblies.
- Large-scale substrate decontamination necessitates either industrial autoclaving or thermal pasteurisation.
- Maintaining a maximum thickness of 50mm is essential to ensure efficient aerobic colonisation by the mycelial network.

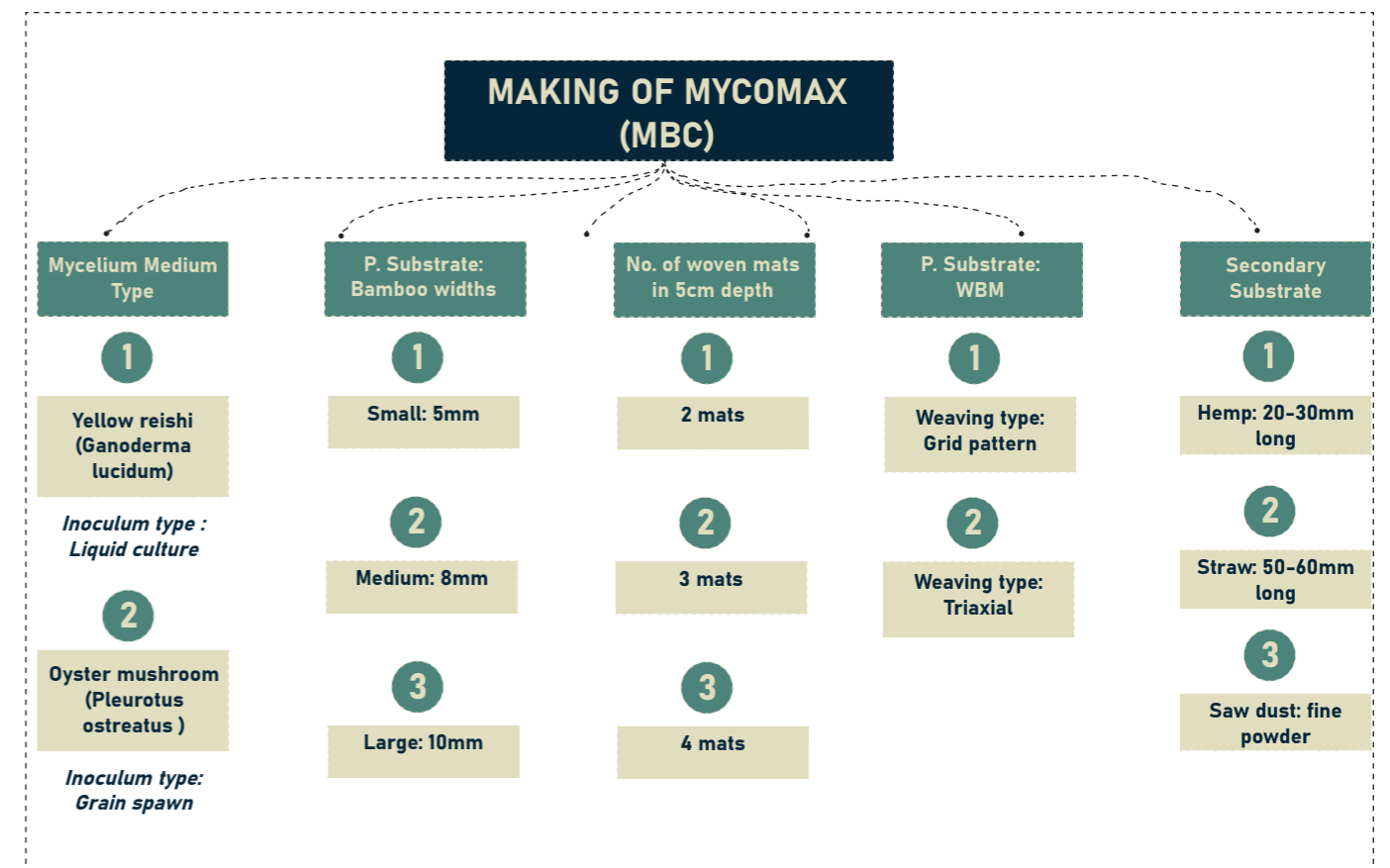


Figure 46: Stage 00 Variables matrix (Author)

# 11.0

## Protocol setup & Experiments

### 11.1 Stage 00: Petri dishes

#### 11.1.1. Objectives

This stage was particularly a stepping stone to determine whether mycelium would successfully grow on this type (Origin type 01) of a bamboo strip. Since the procured bamboo may have contained traces of borax treatment, there was a possibility that it could slow down or negatively affect the growth process and overall colonisation quality. Therefore, all procedures during this stage were carried out under laboratory protocols to maintain the highest possible sterile conditions.

A secondary objective of this phase was to conduct a comparative analysis of three distinct secondary substrates to determine which material facilitated the most robust and uniform mycelial colonisation. Factors kept in mind during evaluation were water retention capacity, sufficient porosity for oxygen to reach to the inner regions of the composite and flexibility with distribution quality of the infill material.

This stage would largely help to narrow down the experimental variables which would also determine feasibility and workability of all the selected materials accordingly.

#### 11.1.2. Autoclave

All the pre-soaked substrates were sealed in a high grade plastic bag using FoodSaver v2860 Vacuum sealer. The sealed bags were then sterilised in an autoclave at 121°C for 30 minutes, followed by a 30-minute cooling period. After sterilisation, the bags were removed and placed inside the flow hood to maintain sterile conditions. A similar sterilisation process was also carried out for the petri dishes and woven bamboo mats (WBM).

During this stage, two important decisions were made. The first was to discontinue the triaxial weave variations, as the priority at this point was to establish and understand the relationship between the bamboo reinforcement and mycelial growth before introducing more complex weaving patterns. The second decision was to temporarily hold the use of grain spawn, as it was not directly contributing to the objectives of this stage. This helped maintain a more controlled and manageable set of specimens for comparison.

Additives such as peptone, malt and agar solutions were eventually ruled out during the experiments. The primary intention of the research was to establish direct interaction and bonding between the mycelium and bamboo strips without introducing an additional coating layer over the bamboo surface. Since bamboo itself is a cellulose-based material and already acts as a potential nutrient source for mycelial attachment, the use of additives was not considered necessary at this stage of the research.

#### 11.1.3. Assembly

Assembly was carried out inside a running flow hood to maintain sterile conditions throughout the process. All equipment, including scissors, tweezers, and the weighing scale, was sterilised using isopropyl alcohol before use.

The assembly ratio consisted of 60 wt% substrate and 40 wt% liquid culture. The liquid culture used was Yellow Reishi, dated



Figure 46: Sealing the substrates (Hemp, Straw, Saw dust) and WBM followed by autoclave (Author)

Table 07: Stage 00 (Petri dishes)- Specimen list (Author)

Specimen	Bamboo width (thickness constant 1mm)	Substrate	Mycelium & Specimen size	Observations
<b>M.St. 01</b> <i>Medium width 8mm, Straw</i>	Medium: 8mm	16g Straw: 50-60mm length	4ml/petri dish <b>Yellow Reishi</b> ( <i>Ganoderma Lucidum</i> ) Liquid Culture dated 16/09/25	Difficulty in controlling the form - straw fibres too long
<b>L.Sa. 02</b> <i>Large width 10mm, Sawdust</i>	Large: 10mm	16g Sawdust: fine powder		Slow growth relatively; lower volume
<b>S.Hst. 03</b> <i>Large width 10mm, Sawdust</i>	Small: 5mm	8g Hemp shives (20-30mm length) ; 8g Straw: 50-60mm length	sourced from Studio Tjeerd Veenhoven;	Consistent growth
<b>M.Hst. 04</b> <i>Medium width 8mm, Hemp &amp; straw</i>	Medium: 8mm	8g Hemp shives: 20-30mm length; 8g Straw: 50-60mm length		
<b>S.Hst. 05</b> <i>Medium width 8mm, Hemp &amp; straw</i>	Small: 5mm	8g Hemp shives: 20-30mm length; 8g Straw: 50-60mm length		
<b>L.H. 06</b> <i>Large width 10mm, Hemp</i>	Large: 10mm	16g Hemp shives: 20-30mm length	100mm (dia) x 15mm (d)	Hemp shows highest growth

16/09/25, indicating that the culture was approximately six months old at the time of inoculation.

The assembly process involved first placing the substrate layer on the weighing scale, followed by positioning the WBM using tweezers to minimise direct contact and contamination risk. A second layer of substrate was then added over the bamboo.

Among the six specimens prepared during this stage (Table 07), three consisted of a combined hemp and straw substrate mixture, while the remaining three used straw, hemp, and sawdust separately as individual substrate types. The liquid culture was applied using a syringe and needle and distributed evenly throughout the specimens within the petri dishes. This process was defined as Inoculation Type 01, in which the inoculation medium is introduced directly during the assembly stage.

### 11.1.3. Incubation

The petri dishes were closed and sealed along the edges using cellophane plastic wrap to minimise contamination and moisture loss. The specimens were then placed inside the incubation fridge, away from direct sunlight, at a controlled temperature between 22°C and 24°C. Low airflow conditions were maintained during incubation, as excessive air movement could introduce unwanted fungal organisms and increase the risk of contamination.



Equipments



Disinfect

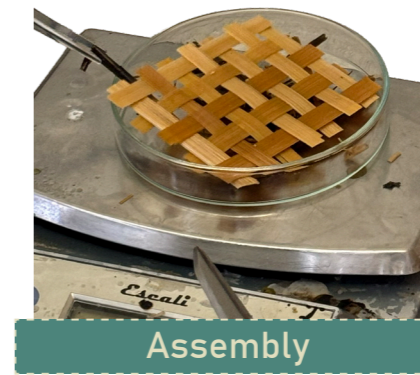
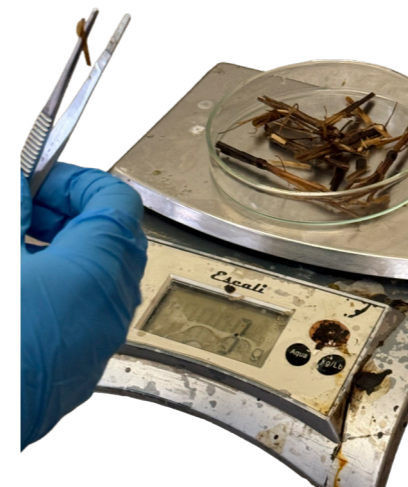
Figure 47: Equipment, setup and disinfecting before inoculation and assembly (Author)



Lab Setup



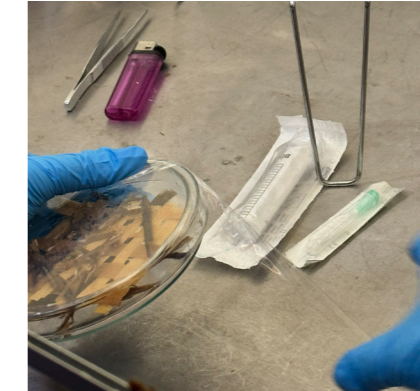
Drawing liquid culture



Assembly



Inoculation type 01: Liquid culture dripped onto the specimen



Incubation

Figure 48: Sealing the substrates (Hemp, Straw, Saw dust) and WBM followed by autoclave (Author)

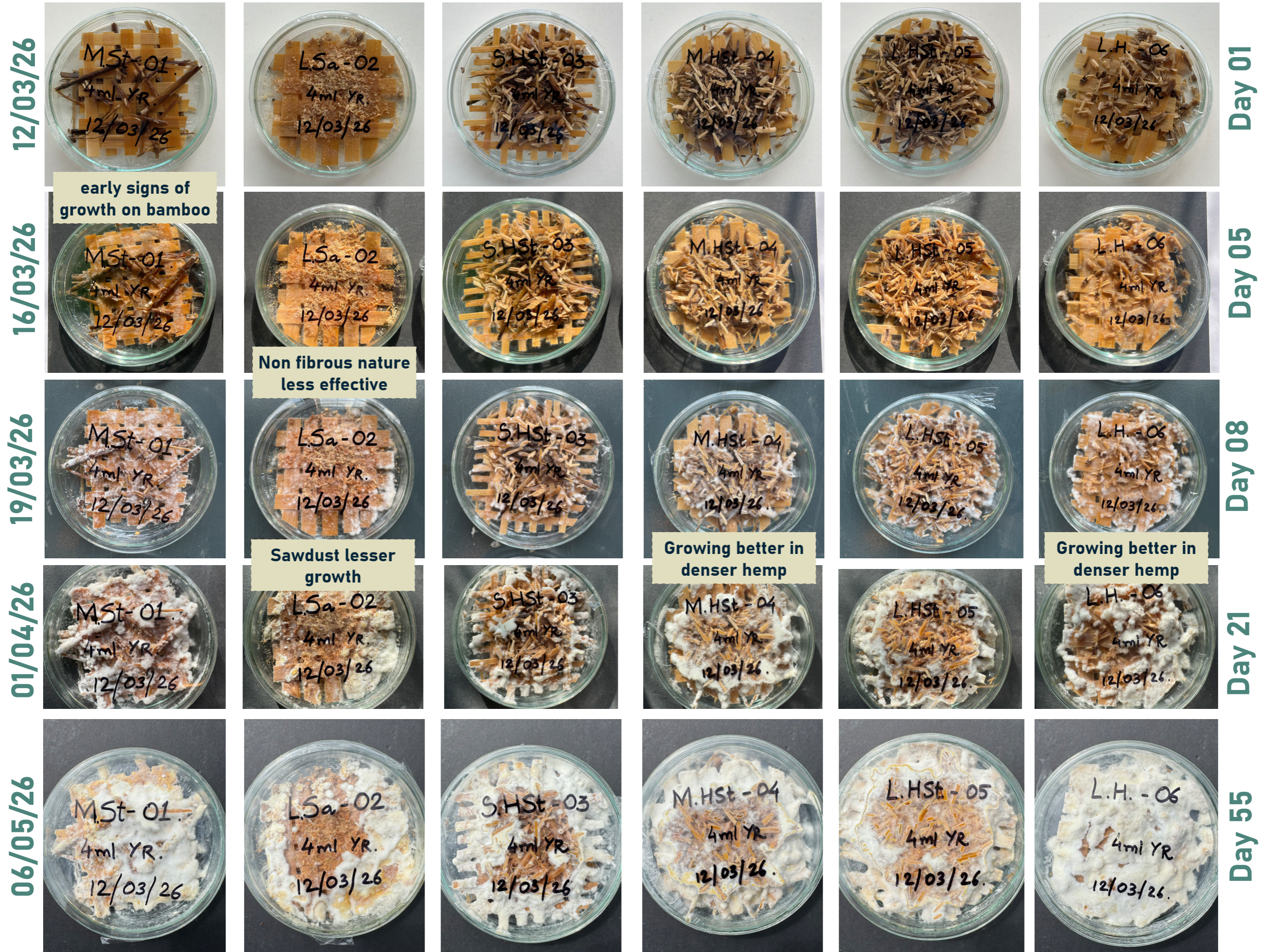


Figure 49: Stage 00: Growth progress (Author)

#### 11.1.4. Observations

During the first 5-8 days there was initial growth that was visible across the specimens. The growth seemed slower than what is commonly described in research papers. Nevertheless, it validated the fact that mycelium was able to adapt to the bamboo mat as a substrate and begin colonisation.

It was also noticed that the mycelium did not grow well (Fig. 51) in areas with too much liquid. The liquid culture that got collected at the bottom showed little to no growth. This was likely because excess moisture reduced airflow and oxygen availability.

Only hemp specimens showed more growth in comparison to mix substrate specimens. The specimen with only saw had the least growth in comparison. Straw was relatively longer to enter spaces between the bamboo thus the growth is spaced out.

Hemp shives of approximately 2-3cm length created a more porous and breathable substrate structure. This improved airflow and oxygen diffusion during mycelial growth. Due to their lower bulk density and coarse particle, it reduced excessive compaction and helped maintain air pockets for healthy colonisation. Insufficient oxygen can slow hyphal growth and might increase contamination risk.

Fine sawdust particles, by comparison, tend to compact during filling. This reduced porosity thus might lead to uneven moisture and restricted oxygen availability in deeper sections of the substrate.



Figure 51: Minimum growth at lower side of the petri dish of the specimen LH-06 due to Liquid culture accumulation (Author)

Long straw fibres (5cm-6cm) proved less effective because their length made it difficult to distribute the material evenly. The fibres tended to bridge across openings and form larger irregular voids. This resulted in inconsistent packing and reduce particle-to-particle contact. Thus, hemp shives provided a more suitable scale, large enough for porosity yet short enough to achieve homogeneous filling within the WBM.

#### 11.1.4. Variables matrix updates

- Number of mats: reduced to 1 and 2, keeping other quantities for further testing and exploration or could also be redundant owing to the 50mm thickness
- Weaving type: Sticking to one simple type grid pattern for a matter of ease during weaving and keeping the variability in control
- Secondary substrate: Choosing Hemp

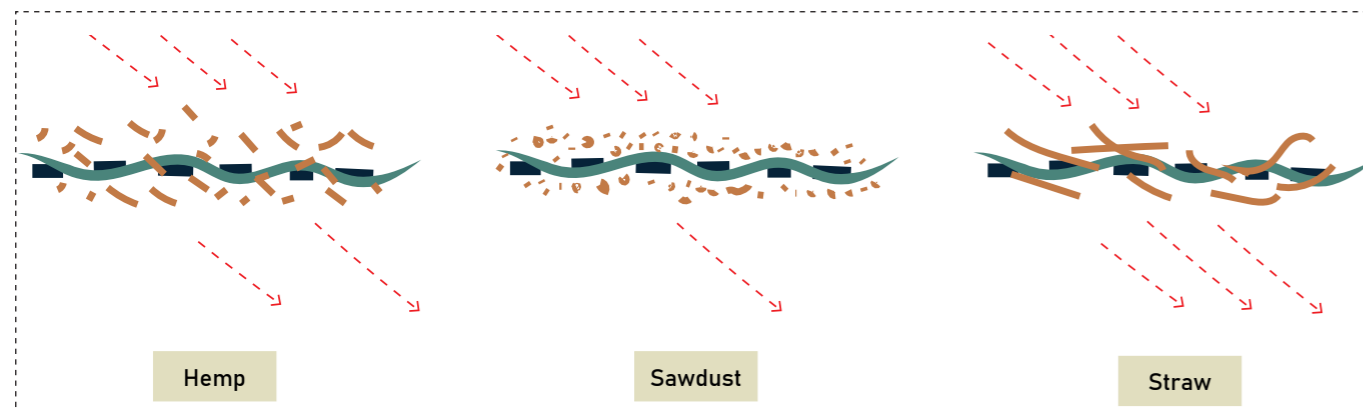


Figure 50: Influence of substrate particle size on porosity and oxygen circulation (Author)

for several reasons due to its particle size characteristics of favourable porosity and density for oxygen diffusion & airflow.

#### 11.1.5. Key takeaways

- Some variables were excluded to keep the study scope controlled, allow clearer comparison and more reliable scientific conclusions
- Substrate porosity and density strongly affected oxygen diffusion and overall mycelial colonisation. Hemp shives proved most suitable for balancing the conditions.
- Liquid culture was less effective when it would get collected at the bottom of the mould and limit the growth

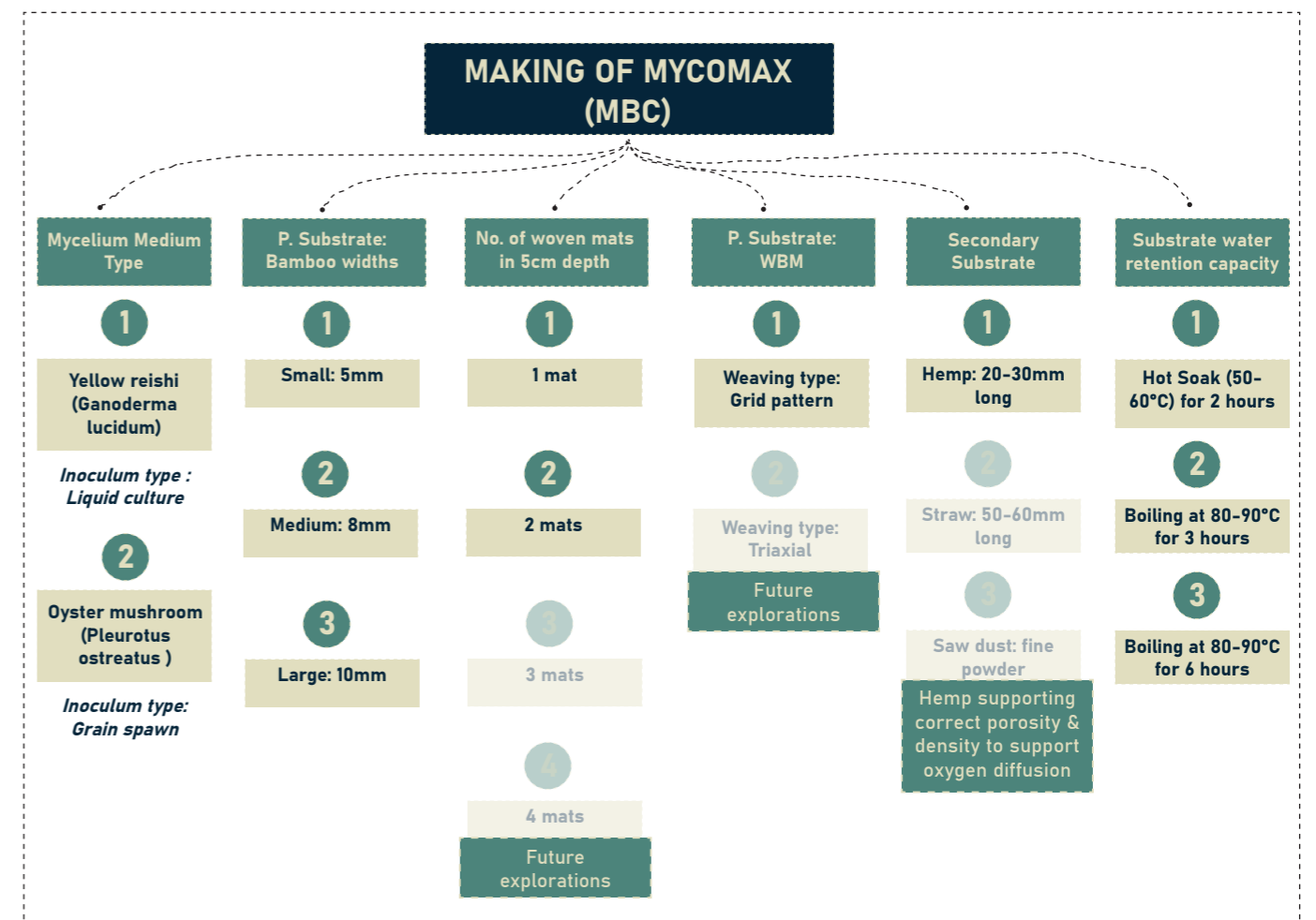


Figure 52: Stage 01 variables matrix (Author)

## 11.2 Stage 01

### 11.2.1. Objectives

This stage focused on **establishing a reliable experimental setup protocol** that could be replicated later for multiple variations and iterations. This was also done to optimise the recipe. During initial trials, one of the main difficulty was the accumulation of liquid culture at the bottom of the substrate mix. This highlighted the need to explore more **effective methods for achieving even distribution of mycelium medium** while mixing with the substrate during inoculation.

This stage was also a good opportunity to **compare the performance of liquid culture** of the strain Yellow Reishi (*Ganoderma lucidum*) and **grain spawn** of the strain Oyster Mushroom (*Pleurotus ostreatus*). The selected fungal species were commonly used in inoculation methods in mycelium-based material research. *Ganoderma lucidum* was chosen based on its application within the gyroid case study (Sharma et al., 2025), while *Pleurotus ostreatus* was used in the Mycomerge case study (Nguyen et al., 2022).

While introducing Woven bamboo mat (WBM) to the 50mm deep composite system, it was important to also **locate their placement** in the depth of the assembly. Additionally, **the number of woven mats** in the composite system was to be investigated, helping identify an appropriate balance between reinforcement density and material performance.

### 11.2.2. Preparation

Since the maximum material depth was fixed at 50mm, it was important to find a mould with suitable proportions for the experimental setup. The selected mould was the IKEA 365+ food container, a rectangular plastic container with a lid and a capacity of 1.0L, measuring 210mm(l) x 150mm (w) and 50mm(d).

The mould was selected for many practical reasons. It was lightweight, stackable



Figure 53: Food container from Ikea used as a mould (Author)

and easy to carry to Groningen from Delft while travelling by train. The size was also compatible to place it in any oven, simple to store during incubation and easily available which helped reduce time required to construct moulds. Since a considerable amount of time was already spent weaving bamboo mats, boiling it and then preparing the hemp substrate before the laboratory work. Using pre-made moulds made the overall process more manageable and efficient.

Bamboo mats were woven according to the dimensions of the mould size in different widths of small (5mm), medium (8mm) and large (10mm) as discussed about the availability in Section 10.1.1. Then it followed the standard boiling process for borax removal before being prepared for laboratory use. For this stage, the hemp substrate was boiled at approximately 50°C - 60°C for 2 hours instead of using the earlier hot water soaking method. This was introduced to observe whether the change in preparation method affected water retention or the overall substrate performance.

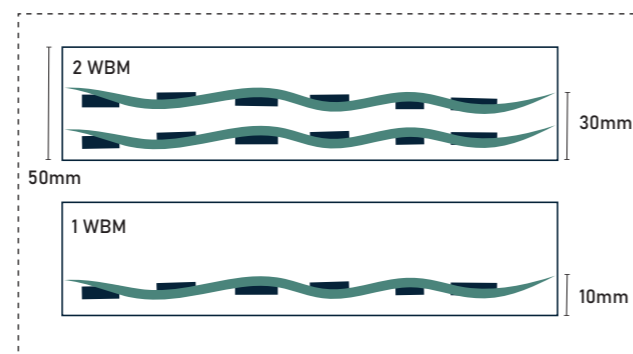


Figure 54: Location of the WBM for 1 and 2 mats (Author)

### 11.2.3. Autoclave

Once the substrates were ready for the lab use, a larger quantity of hemp substrate was to be processed for this stage of the experiment. Due to increased volume, the hemp was divided into two glass jars, each containing approximately 585g of material. The jars were sterilised using Medco portable vertical steam autoclave at 121°C at a pressure of ~1 bar for 30 minutes. The WBMs were also sterilised using the same autoclave process as Stage 00 and were then kept for assembly.

During this process, all the moulds were sterilised using isopropyl alcohol and placed inside the flow hood to dry. All the tools and equipment used during assembly were similarly sterilised and arranged within the flow hood before the inoculation began.

### 11.2.3. Inoculation

To avoid the accumulation of both types of

mycelium mediums at the bottom of the mould, observed previously, inoculation was carried out directly within the sterilised hemp substrate by mixing them thoroughly inside the glass jars. This process was defined as Inoculation Type 02.

Compared to growth rates reported in the literature, the mycelial growth observed during Stage 00 was relatively slow. It took almost 5-6 days to show any growth while alternatively, it should be 2-3 days with some fluffy growth. In addition, both inoculation media used in this stage were approximately six months old, which may have affected their activity and colonisation performance. Therefore, it was decided to increase the inoculation wt% from 40% to 60% to improve growth consistency and colonisation speed.

### 11.2.4. Assembly

As discussed previously, the WBM might perform better when placed closer to the bottom edge of the composite depth, to re-

Table 08: Stage 01- Specimen list (Author)

Specimen	Bamboo strip width (thickness 0.5mm)	No. of woven mats	Mycelium type	Secondary Substrate	Specimen size	Observations
<b>2L.He. 01</b> <i>2 layers WBM, Large width 10mm, hemp</i>	Large: 10mm	2; at 1cm & 3cm from the lower edge	60 wt% to the secondary substrate	Hemp : 30g	<b>Before drying:</b> 210mm (l) x 3.5 mm (w) x 5mm (d)	Hemp inoculation on the same day
<b>1S.He. 02</b> <i>1 layer WBM, Small width 5mm, hemp</i>	Small: 5mm	1; at 3cm from the lower edge	<b>Oyster Mushroom</b> ( <i>Pleurotus ostreatus</i> ) Grain Spawn dated 01/02/26  <i>sourced from Rotterzwam, Rotterdam, Netherlands</i>	Hemp : 30g	<b>After drying (approximation)</b> : 210mm (l) x 3.5mm (w) x 4mm (d)  Each mould will have 3 specimens and each type will have 6 specimens	Grain spawn is necessary to be as fresh as possible for it to grow aggressively on the substrate
<b>2M.He. 03</b> <i>2 layers WBM, Medium width 5mm, hemp</i>	Medium: 8mm	2; at 1cm & 3cm from the lower edge	60 wt% to the secondary substrate	Hemp : 26g		
<b>1M.He 04</b> <i>1 layer WBM, Medium width 5mm, hemp</i>	Medium: 8mm	1; at 1cm from the lower edge	<b>Yellow Reishi</b> ( <i>Ganoderma Lucidum</i> ) Liquid Culture dated 16/09/25 <i>sourced from Studio Tjeerd Veenhoven</i>	Hemp : 36g		Mycelium doesnt grow well in a high liquid concentration area

spond more effectively to tensile forces during bending. Based on this, 2 main types of layer arrangements were executed for the assembly process.

For 2 specimens containing one WBM, the assembly consisted of 10mm of inoculated hemp at the base, followed by WBM and finished with 30mm of inoculated hemp above it. For 2 specimens containing two WBM, the assembly consisted of 10mm of inoculated hemp, followed by a WBM then 20mm of inoculated hemp, a secondary WBM and finally 10mm of inoculated hemp as the top layer. These assembly configurations were prepared using both liquid culture and grain spawn in 2 specimens each respectively to compare their growth behaviour.

### 11.2.5. Incubation

All the moulds were closed and sealed in a plastic bag to minimise contamination and moisture loss. The specimens were placed in the incubation fridge at 22°C - 24°C similar to Stage 00.

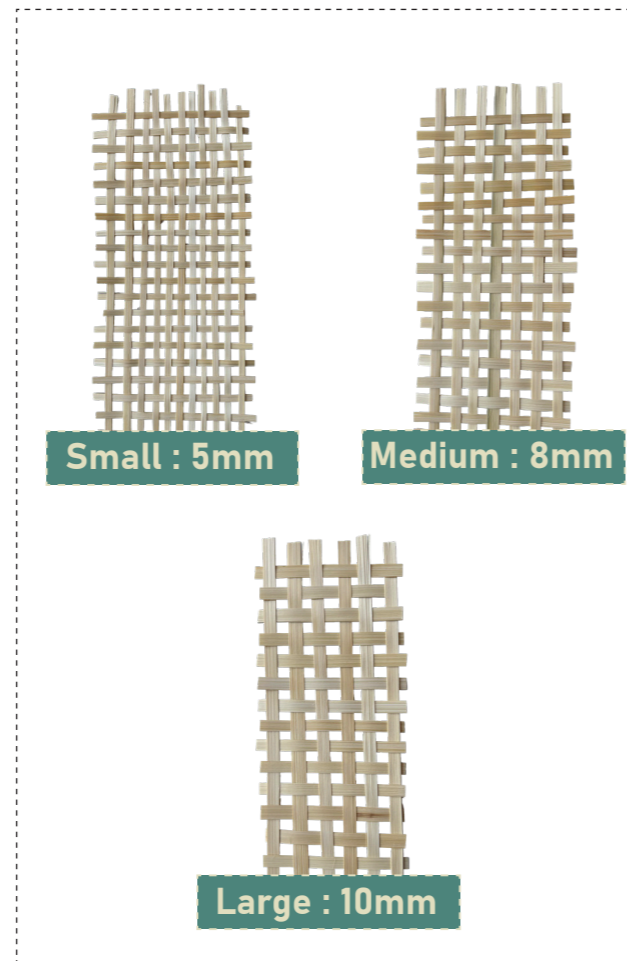


Figure 56: Width variations in WBM (Author)



Figure 58: (1) Autoclave for WBM; (2&3) Equipments and setup; (3) Inoculation with Liquid culture and Grain spawn (Author)

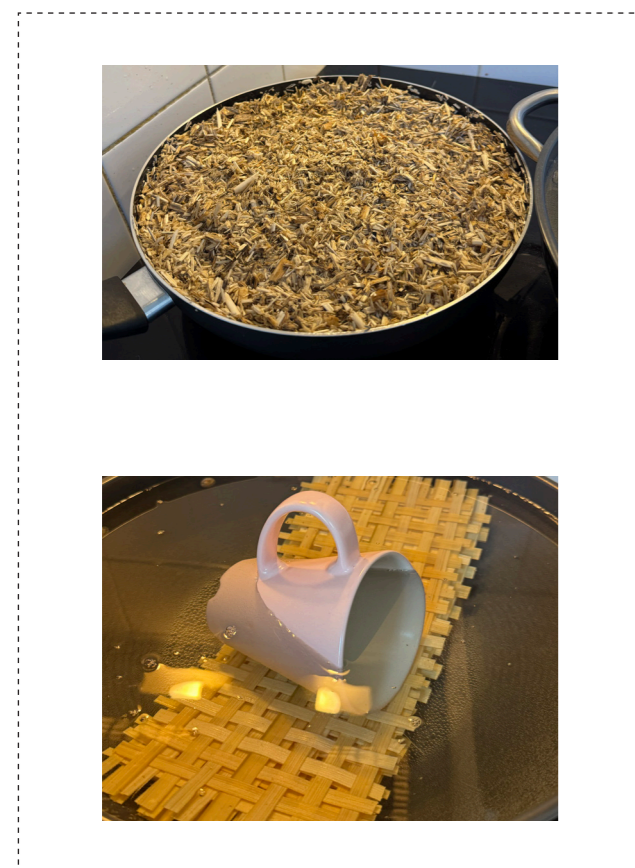


Figure 55: (top) Boiling hemp at 50°C for 2 hours; (bottom) Boiling WBM at 50°C for 2 hours; (Author)

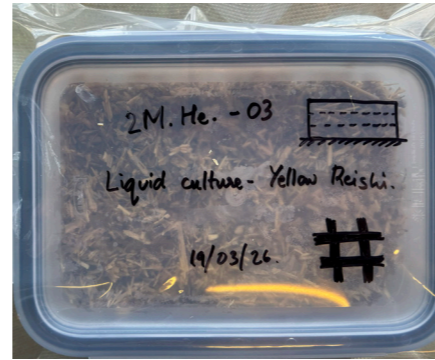
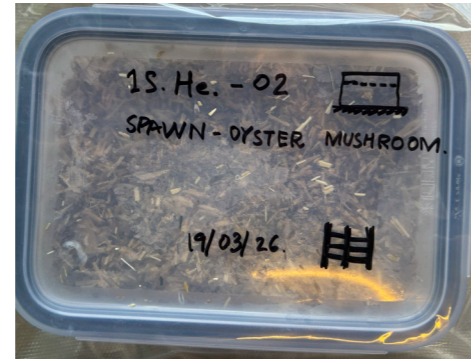
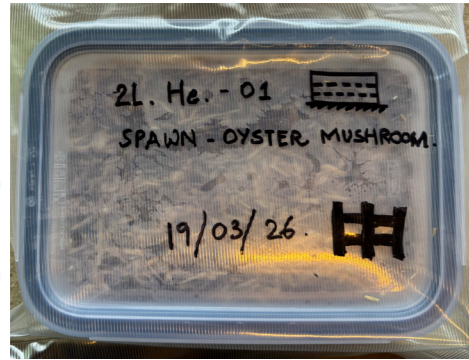


Figure 57: Medco vertical steam autoclave at 121°C for 30 minutes (Author)



Figure 59: Assembly, (1) Mycelium inoculated hemp at 10mm (2) Placing 1 WBM large width 10mm; (3&4) Loosely packed Mycelium inoculated hemp at 10mm (Author)

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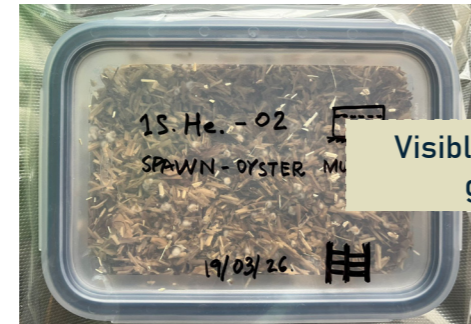
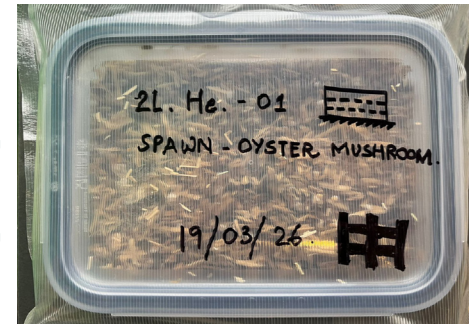


Day 01

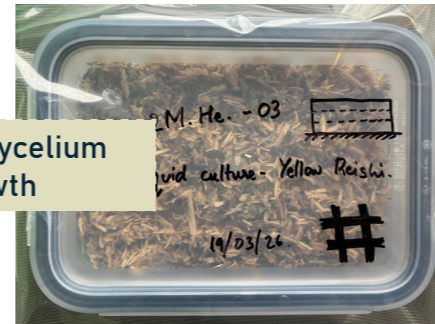


2M.He.03: Liquid concentration on the bottom due to liquid culture, substrate non-compact and loose

24/03/26

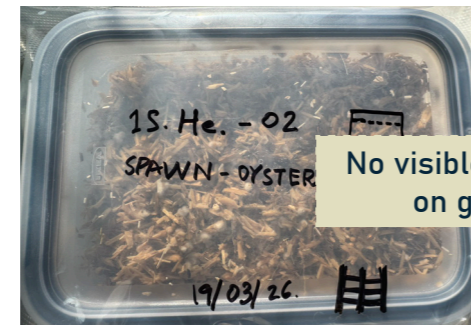
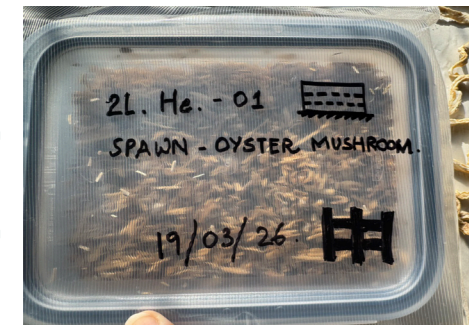


Visible mycelium growth

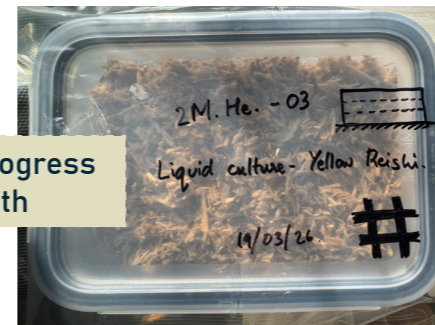


Day 08

01/04/26



No visible progress on growth



Day 16



2L.He.01: loose fibres, minimum growth lesser contact to grain spawn

Introducing openings in the mould

06/05/26



Minimum growth



Visible growth



Day 48

2L.He.01

1S.He.02

2M.He.03

1M.He.04

Figure 60: Stage 01: Growth progress (Author)

### 11.2.2. Observations

During inoculation, the grain spawn exhibited residual clumping. This prevented a homogeneous mixture throughout the matrix. This was similar to Stage 00 where inoculation was carried out during the assembly. This was an attempt to mix the substrate and mycelium prior to assembly for mixing it evenly. Even the liquid culture, after thoroughly mixing it, there was a lot of liquid left at the bottom of the jar. Concluding that it was not the right way to inoculate to evenly mix it.

While consulting with Tjeerd, a key challenge to setting up protocols with new type of moulds is aiming for the right balance between oxygen availability and contamination control. Mycelium requires aerobic conditions and sufficient gas exchange for healthy colonisation. Therefore inoculation bags with a filter proved also quite helpful in the domestic protocol. However it was difficult to replicate something exactly same in

this mould.

Some other issues were very slow growth again, similar to the earlier Stage. This time there was little growth till Day 8 but it remained stagnant until Day 16. Which was quite unfavourable. Therefore sealing it in a plastic was decided to be discontinued for further processes. Both the mediums being 6 months old could also have been another reason for this little growth. Uneven distribution of the medium was also another reason.

It was also noticed that loosely packed fibres are not favourable for even and rich mycelium growth.

#### Choosing Grain spawn over Liquid culture (Refer to section 9.3.3)

- owing to less experience with handling liquid culture, it was a easier choice to use grain spawn.
- Liquid culture requires maintenance in terms of periodic stirring to maintain oxygen

distribution and healthy growth

- Such regular contact without controlled handling conditions would lead to contamination easily as it is highly sensitive. Another important conclusion was that boiling hemp was high energy intensive and was not really making a difference in the results.

The difference in water retention between the 2-hour hot soak and the 2-hour boiling at ~90°C was only 5g for a 10g sample. Although the boiling treatment resulted in slightly greater water uptake, the increase was relatively small compared to the substantially higher energy required for boiling at ~90°C. The hot soak method therefore appeared more energy efficient while still achieving comparable moisture absorption. In addition, the hot soak treatment can be left overnight without continuous energy input, potentially allowing more moisture absorption. In total, there was a weight increase of 40g due to water absorption representing 40% increase compared to its dry weight.

### 11.2.3. Variables matrix updates

Owing to so many moving parts, it was very important to keep the variability in control to finalise a standard protocol to achieve comparable scientific results proving whether WBM really made any difference in the structural performance of the mycelium composite.

- Mycelium medium type: Grain spawn for multiple reasons explained earlier
- Primary substrate: Omitting Medium width (8mm) of bamboo strips to keep the variability in control also it did not have much of a difference from the 5mm due to irregularity and lack of accuracy in widths
- 2 new categories were added, one being whether joining the bamboo mats would make a difference since then it starts acting like a joined composite sandwich system.
- Another category was comparing bamboo

procured from china (type 01) and india (type 02) owing to the delivery a few weeks later. the difference in the type of bamboo was quite difference as the bamboo from type 02 was hand cut instead of being machine cut. it was also natural and not borax treated which might have an impact on the growth of mycelium on the bamboo and also reduce the impact of boiling bamboo like for Type 01.

- Hot soak method for water retention of the hemp shives was conclusive for being the most efficient

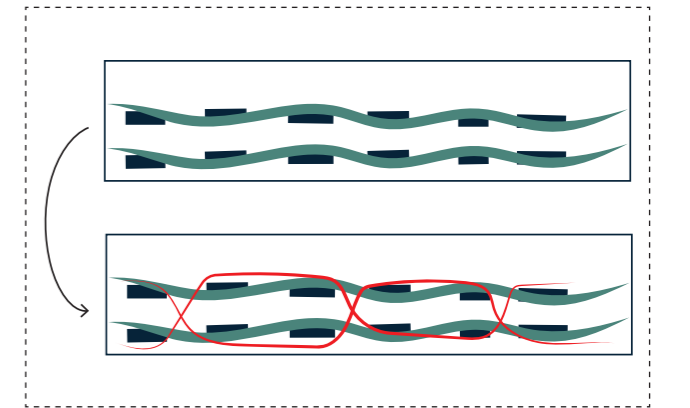


Figure 62: Transition to joining 2 WBM (Author)

### 11.2.4. Key takeaways

- Minimum amount of mycelial growth in current conditions
- Mould type, mycelium age, inoculation process type were some of the factors affecting healthy colonisation
- Hot water overnight soak for water retention in hemp proving to be most efficient
- Introducing ties to join the 2 WBMs for better structural performance
- Addition of bamboo origin type 02, being natural and hand cut bringing in different characteristics
- Discontinuing to seal the moulds in a plastic bag
- Densely packed substrate preferred during assembly

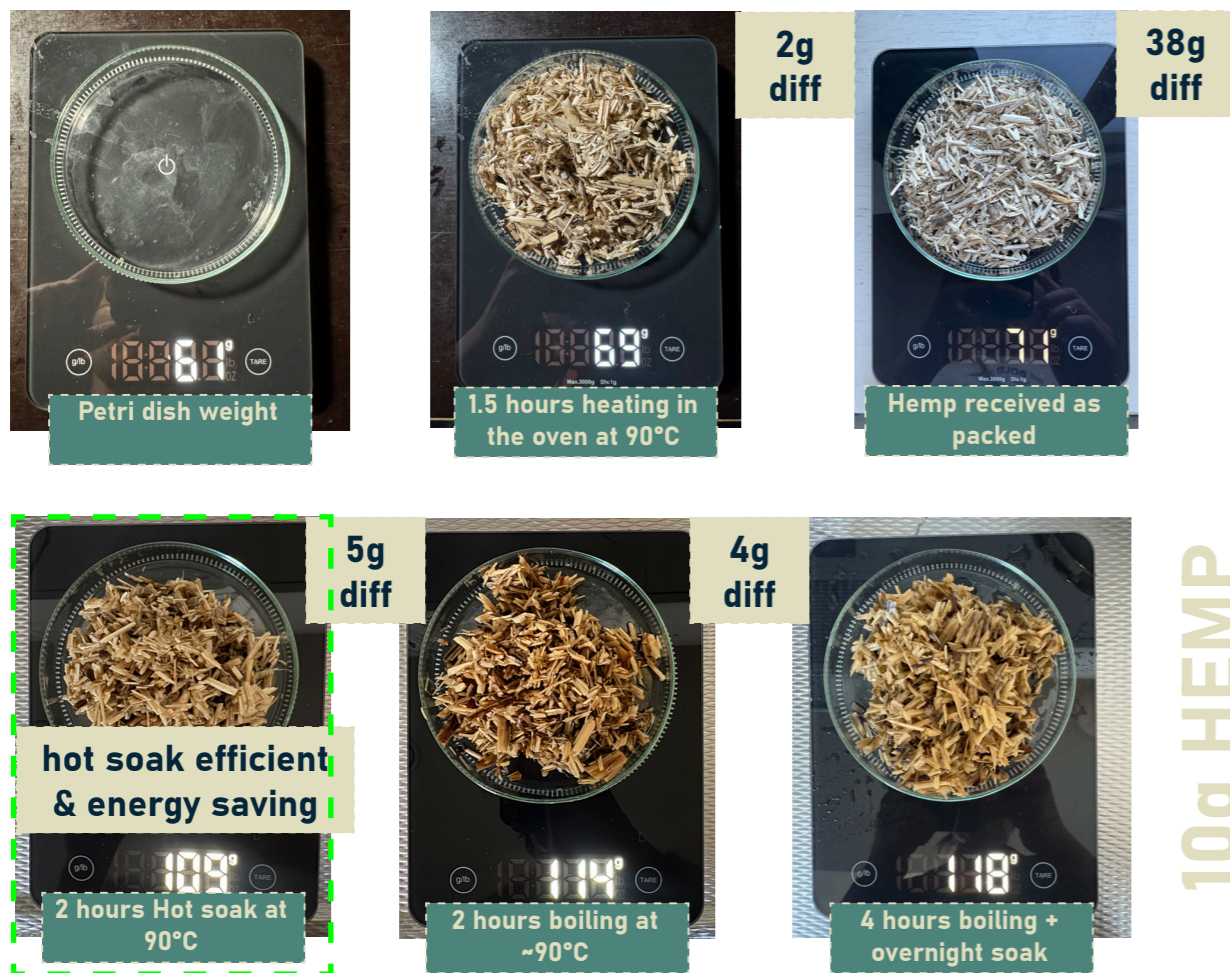


Figure 61: Comparison of treatments for increasing water retention capacity for 10g of Hemp shives (Author)

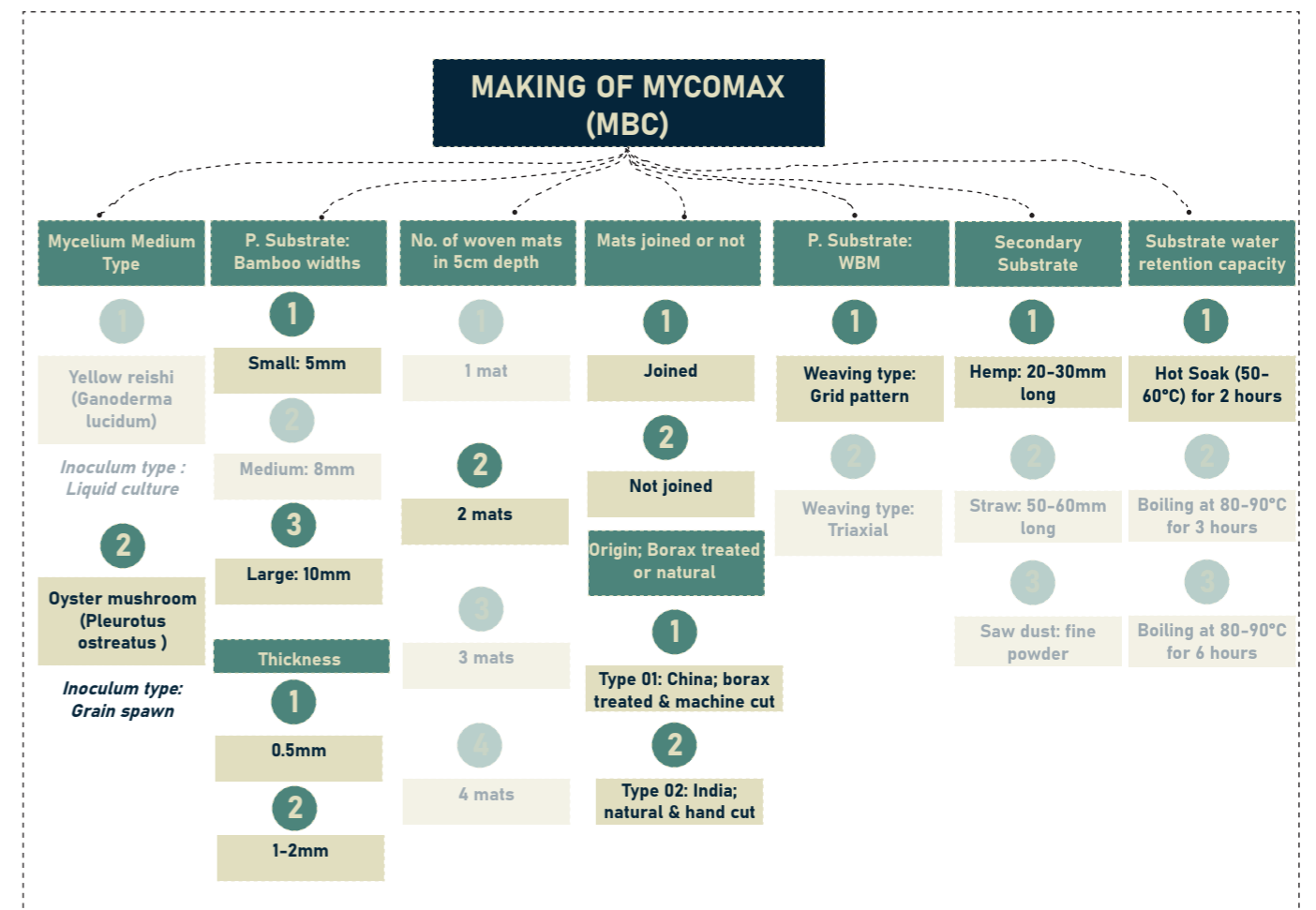


Figure 63: Stage 2A variables matrix (Author)

## 11.3 Stage 02

### 11.3.1. Objectives

In addition to figuring out the efficient way of assembling the favourable composite system for efficient growth, it was also important to find the right way to seal the moulds enough to avoid the risk of contamination, but also allow for oxygen diffusion.

The specimen types were planned to conclude some of the differences like for examples, if there is any difference to the mycelium growth with 2 different types of Bamboo origin as the difference in their characteristic and being natural vs borax treated might also be a deciding factor.

Another important factor was understanding the impact of joining 2 woven mats together, how would they differ in structural performance from mats when not joined. Given the introduction of thicker bamboo strips, does it also govern the structural performance.

### 11.3.2. Methodology A: Preparation (2A)

The preparation for WBMs was very similar to Stage 01 except that it included joining 2 mats together and it also included origin type 02. The weaving process is explained in detail in the earlier section. This resulted in a large pool of varied iterations as listed in the Table 09. All the WBMs Type 01 were boiled for 2 hours as per standard procedure for borax removal.

### 11.3.3. Autoclave & Inoculation

Hemp shives were pre-soaked and sterilised 3 days in advance and inoculated the next day. So the inoculated substrate mix was already ready 2 days prior to the assembly to ensure even mix of mycelium. The mycelium medium used was the grain spawn of oyster mushroom strain which was also procured fresh, so it was only a week old. It was inoculated at 25 wt% of grain spawn to water absorbed hemp shives. While the bamboo

was sterilised at 121°C at ~1 bar for 30 mins, all the moulds and equipments were sterilised and kept to dry in the flow hood.

### 11.3.4. Assembly

Assembly was very straightforward. It was the same layers as Stage 01 but with an addition of the 2 joined mats to be stuff with the inoculated substrate mix. This was layered as 25g of mix, joined mats filled with 25g of mix placing it and then filling the rest with 15g of mix again till the brim. This time the mix was packed with hand with relatively higher pressure to pack the substrate well.

### 11.3.5. Incubation

All specimens were placed in the incubator fridge at 22°C -24°C temperature. This time it was not sealed in a plastic but rather just covered with.

### 11.3.6. Observations: Methodology A

By 10 days, Some of the specimens showed little growth but some did not at all. The mix looked very damp and was very tightly packed so might have started to suffocate as there was almost no loose space left for air to circulate. Therefore, for some ease of oxygen diffusion, one hole was poked into the centre of the box and capped off with a filter. Following 3 days, the growth was still very slow which led to the decision to create 4-5 more holes in each box for better circulation. By this time the damp hemp was sitting in almost no proper circulation to avoid contamination risk for almost 15 days. Moulding had already started and most of the boxes were contaminated by the 20-25 days. Some of them showed positive growth which were eventually saved. The saved boxes were then opened up completely, this resulted a very speedy growth within 4 days. Most of them formed a very young and fresh layer of mycelium all over it but unfortunately some parts on the inside had started contaminating later. This proved that the specimen needs to be exposed to clean air flow and circulation for faster growth with a solution to be contamination free.

From the almost healthy specimens, one of the other major observation while disintegrating the specimens was the delamination at the WBM layer. The joined WBM layer held the mix together very well but unfortunately, since it was packed really close, there was most contamination.

The medium width WBM were two of the top ones that stayed intact with less contamination. One reason majorly being higher porosity for mycelium to grow through and hemp to be infilled in.

### 11.3.7. Methodology B: Updated (2B)

With the given observations, some tweaking was done to the process given that large amount of issues were caused due to lack of oxygen and air circulation. There were some different approaches for few steps.

Some of them being, to start with, grain spawn oyster mushroom was inoculated at 60 wt% with hemp instead of 25 wt%. It also followed Inoculation Type 03 (See section 11.6) that it let it grow for 5 days with the hemp substrate separately. There was quite a lot of growth there. The same plastic food container moulds were used but this time without the lid. They were assembled in the same layers, none of them being joined bamboo, all of them 2 layered WBM with the inoculated substrate mix. The inoculated substrate mix was added with 20% of pre-soaked hemp shives and 10% of wheat flour for it to give a kickstart as an additive to the growth. The specimens were covered using a food-grade polyethylene film with some holes poked into it for constant air circulation and oxygen diffusion. Since they were not sealed completely, They were placed inside the clean room setup with air filter switched on for 5-6 hours in the day to keep the air filtered to reduce contamination risk. It was incubated at an almost constant temperature of ~24°C with the room humidity of ~50% constantly being monitored.

### 11.3.8. Observations: Methodology B

There was white fluffy growth by day 2. A lot of photos were not taken during this process as to keep minimum contact and movement within the space. By the 10th day, it was completely inoculated. There was one or two areas where there was contamination. All the visible contamination was removed. On the 10th day itself they were demoulded, it was quite easy as they were well bonded and compact together. All of them were placed upside down so that it could build a new mycelial layer before the deactivation.

### 11.3.8. Key takeaways

- Inoculation type 03 (Fig. 65) evenly mixes the substrate with mycelium
- Inoculating at 60 wt% is really effective as it overpowers and colonises rapidly, there is less chance of contamination
- Adding wheat flour is a good acceleration to kickstart the growth
- To stabilise and increase the ratio of secondary substrate, 20 wt% is added during assembly
- Packing is done milder than Stage 02 to allow air circulation and avoid moulding due to excess water
- Striking the right balance with sealing the final specimen and keeping some pores open for aerobic respiration
- Additive as wheat flour was a good starter for better mycelium growth

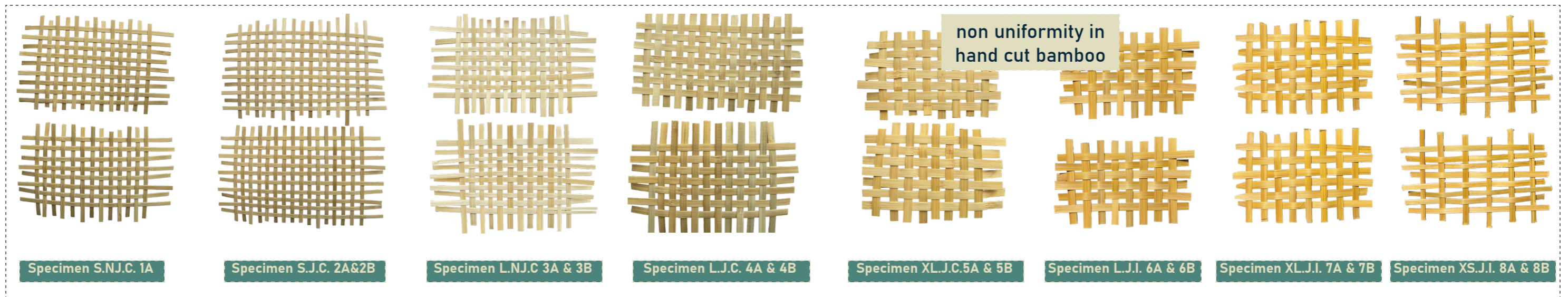


Figure 64: Woven bamboo mats for Stage 2A (Author)

Table 09: Stage 2A- Specimen list (Author)

Specimen	Bamboo width & thickness	Joined or Non Joined	Bamboo Origin & Characteristics	Mycelium type	Assembly Weight pattern	Specimen size	Observations
<b>S.NJ.C.1A</b> <small>Small width 5mm, non-joined, China origin type 01</small>	Small: 5mm;	Non-joined	Treated with Borax; Machine cut strips	25 wt% to the secondary substrate	<b>Layer 01:</b> 250g substrate (densely packed)	<b>Before drying:</b> 210mm (l) x 3.5 mm (w) x 5mm (d)	Irregular thicknesses of the hemp filled in between 2 mats
<b>S.J.C. 2A &amp; 2B</b> <small>Small width 5mm, joined, China origin type 01</small>	Thickness: 0.5 mm						
<b>L.NJ.C.3A &amp; 3B</b> <small>Large with 10mm, non-joined, China origin type 01</small>	Large: 10mm; Thickness: 0.5 mm	Non-joined	Non-treated; Hand cut natural bamboo	sourced from Rotterzwam, Rotterdam, Netherlands	<b>Layer 03:</b> 200g substrate (densely packed to the brim)	Each mould will have 3 specimens and each type will have 6 specimens	Hemp inoculated 2 days prior with Oyster mushroom grain spawn
<b>L.J.C.4A &amp; 4B</b> <small>Large with 10mm, joined, China origin type 01</small>	Large: 10mm; Thickness (X): 2mm	Joined					
<b>XL.J.C.5A &amp; 5B</b> <small>XLarge with 10mm, 2mm thickness, joined, China origin type 01</small>			<b>L.J.I.6A &amp; 6B</b> <small>Large width 10mm, joined, India origin type 02</small>	<b>XL.J.I.7A &amp; 7B</b> <small>XLarge width 10mm, 2mm thickness, joined, India origin type 02</small>	<b>XS.J.I.8A &amp; 8B</b> <small>XSmall width 5mm, 2mm thickness, joined, India origin type 02</small>		



Figure 65: Stage 2A: Preparation before inoculation (Author)



Figure 66: Stage 2A: Assembly (Author)

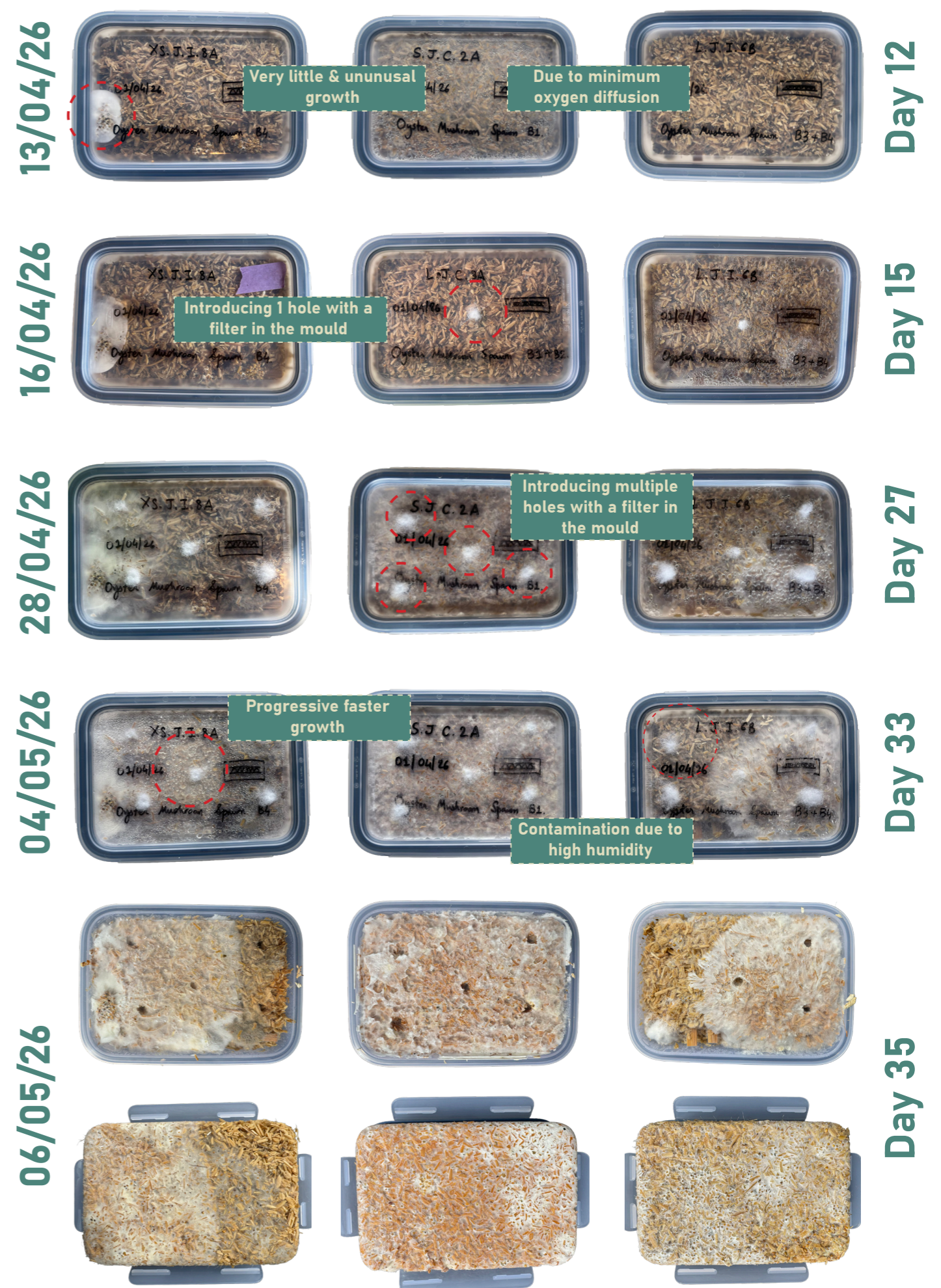


Figure 67: Stage 2A: Growth progress (Author)



Figure 68: Stage 2B: Inoculation, Preparation & Assembly (Author)



Figure 69: Stage 2B: Incubation in the clean box at 22°C - 24°C (Author)

## 11.4 Post-processing

All the samples from Stage 00 were not processed and only preserved in the petri dish for further inspection under the microscope. All the fully grown samples from Stage 01, Stage 02 were demoulded together and processed after that.

### 11.4.1. Observations during Demoulding

#### Stage 01:

Specimens 2M.He.03 and 1M.He.04, (inoculated using liquid culture medium) reinforced with 2 non-joined WBMs and 1 WBM respectively showed some growth. However, during the demoulding process, both specimens delaminated at the interface of the WBM. The lower portions of the composite remained soft and mushy due to the accumulation of excess liquid culture residue within the substrate. This happened mostly because the top region was relatively drier and positioned closer to the oxygen source, there created favourable

conditions for growth.

Alternatively, the remaining two specimens from Stage 01 that were inoculated using grain spawn did not show visible mycelial growth. As a result, these samples were discontinued from further stages of the experiment.

#### Stage 2A:

Since new mycelial growth had developed along the edges, demoulding was supposed to be done carefully. The samples had to be gradually separated from the edges using a thin steel edge to prevent cracking and maintaining the integrity of the composite. Specimens with joined WBM, were delaminated from the lower half of the composite, proving the joining of 2 WBM a considerable choice.

One of the most significant observations was the influence of bamboo strip width and origin on the structural behaviour. Specimens with L width of 10mm with origin

Table 10: Stage 2A: Conditions after demoulding (Author)

Sr. no.	Condition	Stage 02A: ID	Joined/NJ	Width	Thickness	Origin
1	Completely intact	L.J.I.6B: B3+B4	Joined	L (10mm)	0.5mm	2
2	Partially delaminated at WBM	XS.J.I.8A: B4	Joined	XS (5mm)	2mm	2
3	Completely intact but minimum growth	XL.J.C.5B: B3	Joined	XL (10mm)	2mm	1
		L.J.I.6A: B3	Joined	L (10mm)	0.5mm	2
4	Completely delaminated at WBM	S.J.C.2A: B1	Joined	S (5mm)	0.5mm	1
		L.J.C.4B: B2	Joined	L (10mm)	0.5mm	1



1 L.J.I.6B Completely intact



3 L.J.I.6A Completely intact, minimum growth



4 S.J.C.2A Completely delaminated



2 XS.J.I.8A Partially delaminated



1M.He.04 Complete delamination



2M.He.03 Complete delamination



Figure 70: Stage 01: Delamination conditions after demoulding (Author)



Figure 71: Stage 2A: Delamination conditions after demoulding (Author)

type 02 (India) or thicker strip with origin type 01 (China) were found to be completely intact and no delamination. While the specimens, which had small width of 5mm and thinner strips had more results of delamination despite visible mycelial growth. This largely concludes that larger (10mm width) specimens which had larger gaps had a stable substrate distribution and sufficient mycelial colonisation. Delamination with smaller specimens indicated insufficient bonding between the substrate and WBM. Larger gaps also mean better airflow, therefore rich in oxygen diffusion.

Furthermore, strip from origin type 02 showed better results, this must be because it was natural and hand cut, open fibres for mycelium to colonise more effectively in comparison to a machine cut processed strip from origin type 01.

**Stage 2B:**

Demoulding (Fig. 73) was comparatively easier than the previous stages. The specimens only required slight deformation of the mould edges before they could be removed smoothly by inverting the mould upside down. The samples remained under incubation for 11 days and were then demoulded for an additional 2 days to allow external mycelial skin formation.

Many of the specimen edges showed gaps

and incomplete mycelial colonisation, likely due to insufficient hemp substrate density near the corners, around the bamboo and boundaries of the mould. Mild contamination was also observed along some edges, which may have resulted from less effective sealing compared to fully enclosed container systems.

In one of the specimen, delaminated broken edge formed during demoulding were observed to partially regrow and reattach themselves to the main body after two additional days of growth. This demonstrates the self-binding capability of the mycelium network. It was also consistently observed that central regions of the specimens showed healthier and denser mycelial growth, while the the corners and edge regions were more prone to defects, incomplete colonisation and contamination.

**11.4.2. Thermal Deactivation Parameters**

The most commonly referenced temperature range for mycelium deactivation in existing literature for similar composition was between 40°C and 60°C, typically maintained for at least 18-24 hours and in some cases up to 48 hours. The required duration is not standard and changes case to case basis due to large variability of components. It largely depended on the thickness, porosity and moisture retention capacity of the composite. To keep a track of the right drying



Figure 73: Stage 2B: Demoulded for mycelial skin formation before 2 days before deactivation (Author)

and deactivation, the goal was to achieve weight reduction of approximately 45-50%, indicating sufficient moisture removal and stabilisation of the material.

**Stage 01 & 2A:**

The Memmert 600 A universal laboratory oven located at the Pavement Engineering Lab within the Faculty of Civil Engineering and Geosciences was used to deactivate all specimens from the Stage 01 and Stage 02A. During the process, the oven temperature was maintained at 60°C with the airflow set-

ting adjusted to level 4 out of 6 to support gradual drying and moisture removal.

After deactivation, the specimens appeared very dry and flaky, largely due to the insufficient and uneven mycelial growth observed during these stages. In areas where the mycelium had not effectively bonded the substrate, the hemp became completely dry and began to disintegrate (Fig. 72). The delaminated specimen with a thickness of approximately 25mm appeared fully dry and was very lightweight. The specimens 50mm thick were fully dry from the outside but after a

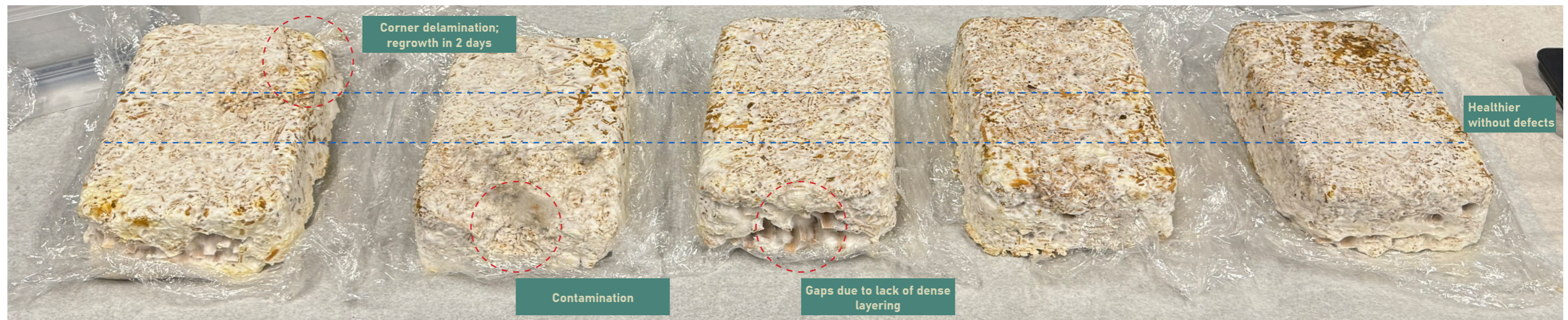


Figure 72: Stage 2B: Right before deactivation (Author)

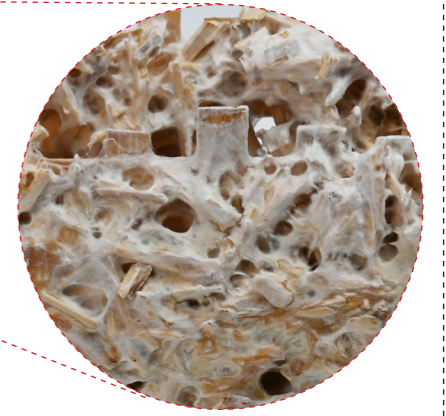
Stage 1 & 2A: Before



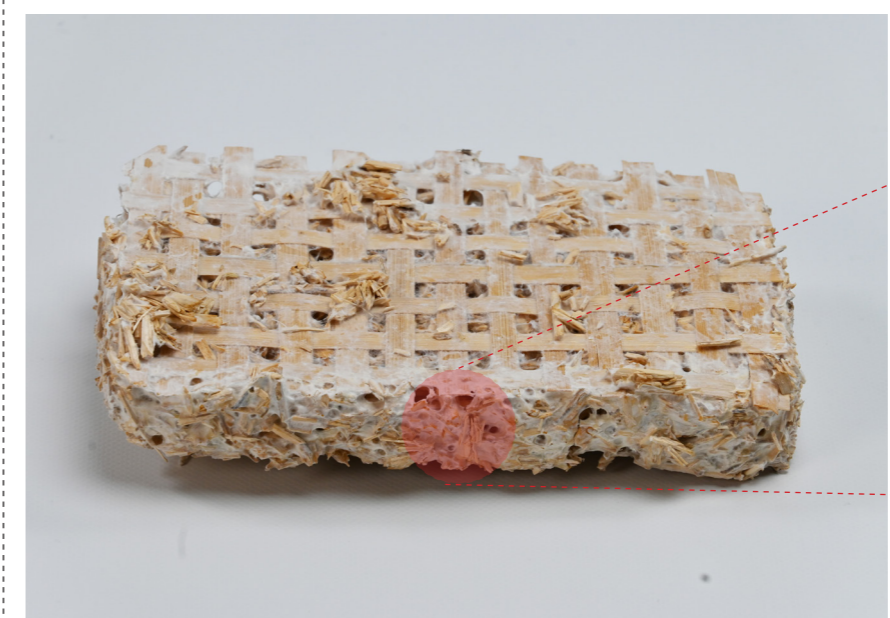
Stage 1 & 2A: After



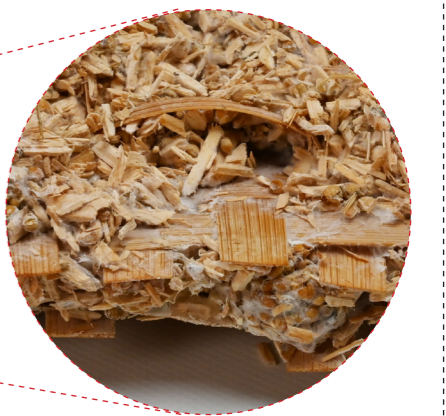
Figure 74: Stage 1 & 2A: Thermal deactivation for 18 hours at 60°C (Author)



Minimum mycelial growth



WBM and mycelial binding



Ties holding the substrate and mycelial growth

Figure 75: Specimens after Thermal deactivation from Stage 01 & 2A (Author)

Stage 2B: Before



Stage 2B: After



Figure 76: Thermal deactivation for 24 hours at 40°C (Author)



Figure 77: Ther 40°C (Author)



Figure 78: Thermal deactivation for 24 hours at 40°C (Author)

few days, there were some signs of continued growth and mushroom-like odour were still observed in the thicker specimens. In one of the cases, the smell also suggested possible contamination within the centre of the composite.

### Stage 2B:

During this stage, all specimens were at an average thickness of 50mm and given with the experience of the prior stage, it was important for drying to happen gradually and evenly. They were therefore deactivated at a constant of 40°C for 24 hours.

Following deactivation, the outer surfaces

Table 11: Water mass loss during deactivation: Stage 2B (Author)

Sample	Before	After	Mass Lost	% Lost
M05.H.M.C.	379	217	162 g	42.70%
M04.H.M.I.	360	202	158 g	43.90%
M02.H.S.I.	333	195	138 g	41.40%
M01.H.00	345	201	144 g	41.70%
M03.H.S.C	339	169	170 g	50.10%

became dry and visibly shrunk. In several areas, the bamboo reinforcement also showed signs of stress caused by the shrinkage of the surrounding mycelium-bound substrate.

All the specimens were weighed before and after the deactivation process. The measured weight reduction was generally within the target range of approximately 45-50% (Table 11), beyond which the material risked becoming excessively brittle and overly dry. Despite the reduction in moisture content, it remained difficult to confirm whether the central regions of the specimens had dried completely.

The deactivation process was eventually stopped due to visible cracking and shrinkage in the outer mycelial skin, along with concerns that continued drying could lead to excessive brittleness.

### 11.4.3. Band Saw Cutting

The composite system behaved similarly

to soft wood or dense cork, based on this behaviour a band saw was selected as the primary cutting tool for compression test specimen preparation. A key advantage of using the band saw was the downward motion of the blade, which helped keep the composite compressed against the table surface during cutting. This reduced the risk of layer separation and delamination within the composite.

Cutting was carried out using the HEMA H500 Vertical Woodworking Band Saw (Fig. 79) in the wood workshop of the Faculty of Architecture and the Built Environment. It had a high blade speed of approximately 700-1500 m/min reducing the formation of rough or ragged cuts along the surface. To achieve consistent specimen dimensions, the grown material composite system was cut into cubes measuring approximately 5cm due to its natural irregular geometry. Safety glasses and a face mask were used throughout the cutting process as the material produced fine fibrous particles that could cause irritation.



Figure 79: Hema band saw at the Model hall-wood workshop, Faculty of Architecture (Author)

### 3.2.3 Key takeaways

- The hemp substrate exhibits a high water retention capacity, necessitating precise moisture control prior to inoculation.
- High-density manual compaction is essential to facilitate a cohesive, structurally dense hyphal network.
- Continuous gas exchange, regulated by the porosity of the matrix, is critical for healthy mycelial growth.
- Higher carbon dioxide concentrations within the formwork severely stagnate mycelial growth.
- The biological matrix requires a near-neutral pH; highly acidic or alkaline environments actively suppress mycelial growth.
- Excessive water retention in the hemp, compounded by airtight formwork, displaced available oxygen, inducing localized anaerobic conditions that stunted colonization.

## 11.5 Compression tests: Stage 2B

### 11.5.1. Introduction

Specimens during Stage 01 and Stage 2A were excluded from the compressive testing dataset due to insufficient structural integrity. Stage 01 specimens experienced severe delamination and disintegration caused by contamination, resulting in brittle material behaviour and preventing reliable mechanical characterisation. Similarly, most Stage 2A specimens were unsuitable for standardised compression testing, which required the preparation of 50 mm cube specimens. While cutting the specimen to size, many samples disintegrated, indicating inadequate mycelial binding within the substrate matrix.

However, two Stage 2A specimens demonstrated sufficient internal bonding and remained structurally intact. To preserve their integrity, these samples were tested in their original dimensions, as discussed in Section 14.2 with other specimens from Stage 03, rather than being cut into standard cubes. Due to the irregular geometry of the grown biological material, the dimensions of the final specimens varied slightly between batches in order to obtain the most orthogonal geometry possible. The standard testing size was defined as  $n = 6$ , except for groups M01 and M03, where the sample size was reduced to  $n = 4$  due to localised contamination and handling damage.

### 11.5.2. Testing standards and equipments

Compressive testing for all Stage 2B specimens was conducted in accordance with ASTM D1621, the standard testing method for evaluating the compressive properties of rigid cellular plastics. This standard is commonly used within current mycelium composite research due to the foam-like behaviour of MBC materials. The protocol requires specimens to possess parallel loading surfaces and a relatively uniform cross-section, with an aspect ratio close to 1:1. Based on these requirements, 50 mm cube specimens were adopted as

the standard testing geometry.

Mechanical loading was applied under displacement-controlled conditions at a constant piston speed of 0.3 kN/sec. To prevent damage to the testing equipment and ensure safe operation, the compression cycle was manually terminated when the plate clearance reached approximately 30 mm. All tests were conducted using a MATEST Servo-Plus Evolution Automatic Hydraulic Compression Testing Machine, calibrated and serviced by MACBEN, located within the Stevin Laboratory at the Faculty of Civil Engineering and Geosciences.

### 11.5.3. Objectives

The primary objective of this mechanical testing phase was to evaluate the influence of the woven bamboo reinforcement on the internal load distribution and overall structural capacity of the composite matrix under compressive stress. Furthermore, the research aimed to establish the optimal geometric parameters for the reinforcement scaffold, specifically analysing the cell grid size, strip width, and strip thickness, while simultaneously assessing the material viability of two distinct geographical bamboo origins.

Consequently, the Stage 2B compressive testing protocol was designed to systematically isolate and evaluate these variables through three primary comparative analyses:

- Reinforcement: The mechanical performance of the unreinforced substrate compared against the bamboo-reinforced composite system.
- Scaffold geometry: The structural impact of the grid cell size and interfacial binding area, specifically contrasting small width (5 mm) bamboo strips against large width strips (10 mm).
- Processing difference: The structural efficacy of Bamboo origin type 01 (China) versus Bamboo origin type 02 (India).

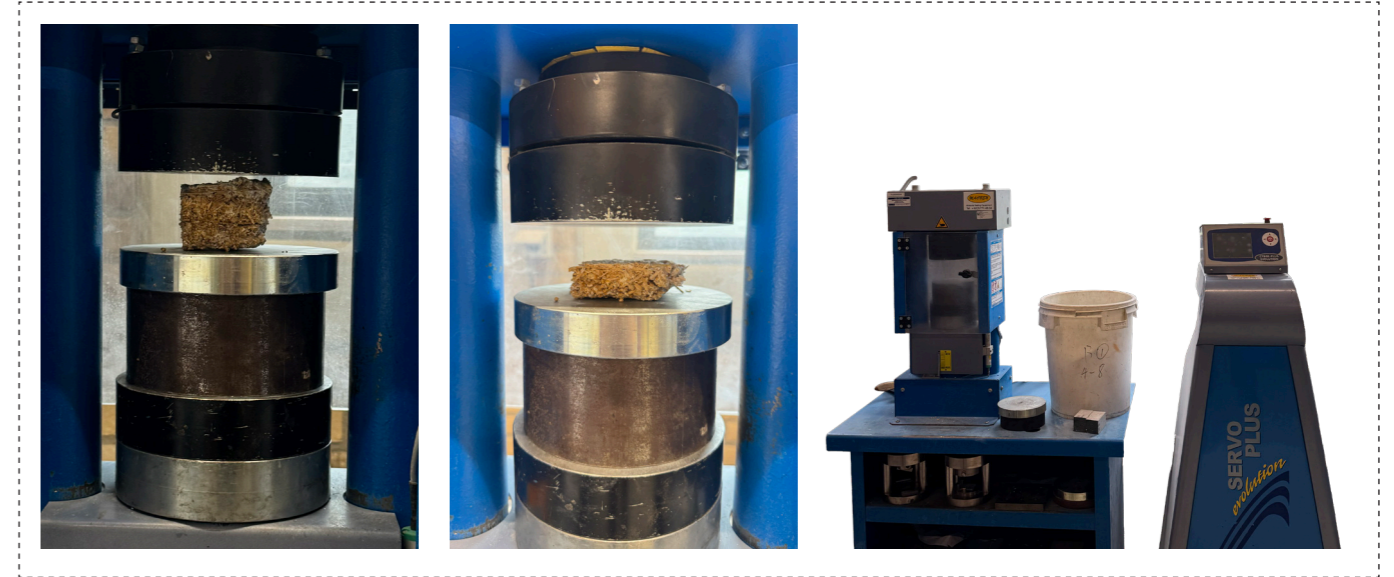


Figure 80: (left, centre) Deformation of the specimens after compression test; (right) MATEST Servo-Plus Evolution Automatic Hydraulic Compression Testing Machine (Author)

### 11.5.4. Results and observations

#### Yield stress distribution by specimen group:

Before analysing the specific mechanical behaviors of the composite, the overall compressive strength results are summarised and compared using a box-and-whisker plot (Fig. 81). Mycelium and bamboo are natural, biological materials and they exhibit inherent growth variations and physical irregularities. Consequently, evaluating the statistical spread of the testing data is just as critical as evaluating the mean values. The box plot effectively visualises the median compressive

strength, the overall data variance the presence of any structural outliers within each specimen group. Specifically, the distribution highlights a variance in the specimen group M05, which exhibits a much larger statistical spread. Alternatively, groups M03 and M02 demonstrate highly clustered data points, indicating a tighter range and structural consistency. By mapping these distributions, this graphical analysis provides a clear, macroscopic comparison of structural consistency, highlighting exactly how reliable the different bamboo reinforcement strategies are when compared to the unreinforced specimen group M01.

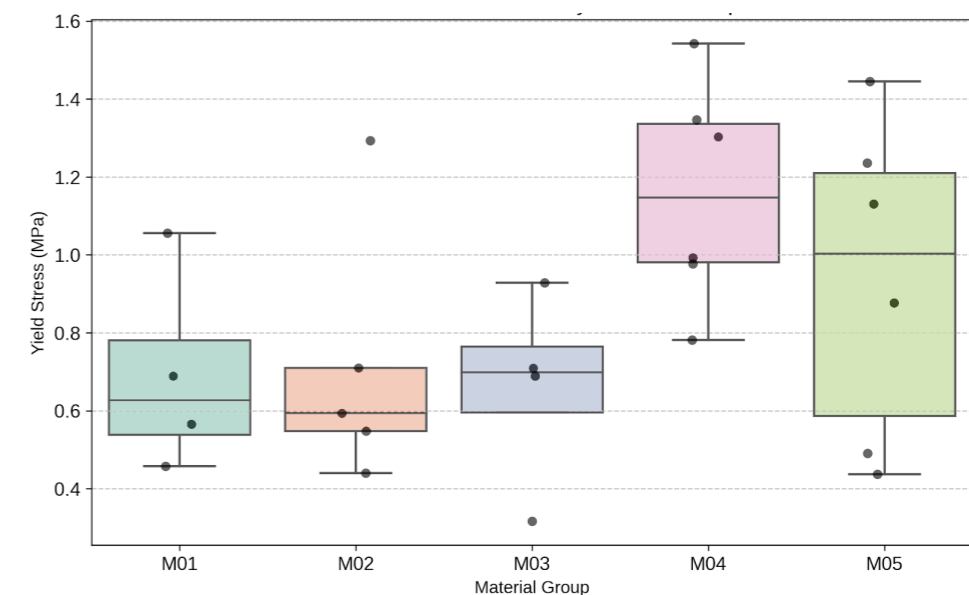


Figure 81: Comparative yield stress distribution of all the specimens group from Stage 2B (Author)

Table 11: Stage 2B- Specimen list with their resulting mechanical characteristics (Author)

Specimen type	Sr. no.	Deformation (mm)	Fmax (kN)	Yield strength (MPa)	Mean Compressive strength [%] MPa	Mean Density [kg/m <sup>3</sup> ]	Location of the piece	Observations
M.01.H.00 <i>(Only hemp; no bamboo)</i>	1	10.509	1.098	0.458	0.692	207	corner	disintegration at the corners
	2	12.38	1.357	0.565			corner	disintegration at the corners
	3	15.306	2.535	1.056			centre	high mycelial growth
	4	13.747	1.653	0.689			centre	light disintegration
M02. H.S.I. <i>(Hemp, Small width 5mm, India origin type 02)</i>	1	8.009	1.055	0.44	0.717	201	corner	complete disintegration and delamination
	2	10.349	1.425	0.594			corner	disintegration at the corners
	3	10.206	1.314	0.548			corner	complete disintegration and delamination
	4	14.379	3.103	1.293			centre	intact
	5	11.785	1.703	0.709			corner	light disintegration
M.03.H.S.C. <i>(Hemp, Small width 5mm, China origin type 01)</i>	1	12.772	2.227	0.928	0.661	179	corner	air pockets before testing
	2	11.954	1.653	0.689			corner	delamination; disintegration at the corners
	3	6.914	0.759	0.316			centre	high mycelial growth
	4	10.91	1.703	0.709			centre	complete disintegration and delamination
M04. H. L. I. <i>(Hemp, Large width 10mm, India origin type 02)</i>	1	14.828	3.128	1.303	1.157	208	corner	light disintegration
	2	15.074	3.233	1.347			corner	delamination
	3	12.434	2.344	0.977			corner	delamination
	4	11.399	1.875	0.781			corner	complete disintegration and delamination
	5	12.005	2.381	0.992			centre	light disintegration
	6	14.202	3.701	1.542			centre	light disintegration
M05.H.L.C. <i>(Hemp, Large width 10mm, China origin type 01)</i>	1	13.235	3.467	1.445	Highest yield strength		centre	disintegration at the corners
	2	12.594	2.714	1.131	0.936	223	centre	disintegration at the corners
	3	12.211	2.104	0.877			corner	uneven deformation due to large air pockets
	4	8.138	1.049	0.437			corner	mycelial growth minimum
	5	8.003	1.178	0.491			corner	delamination; disintegration at the corners
	6	15.049	2.967	1.236			corner	high mycelial growth; highest deformation due to more air pockets

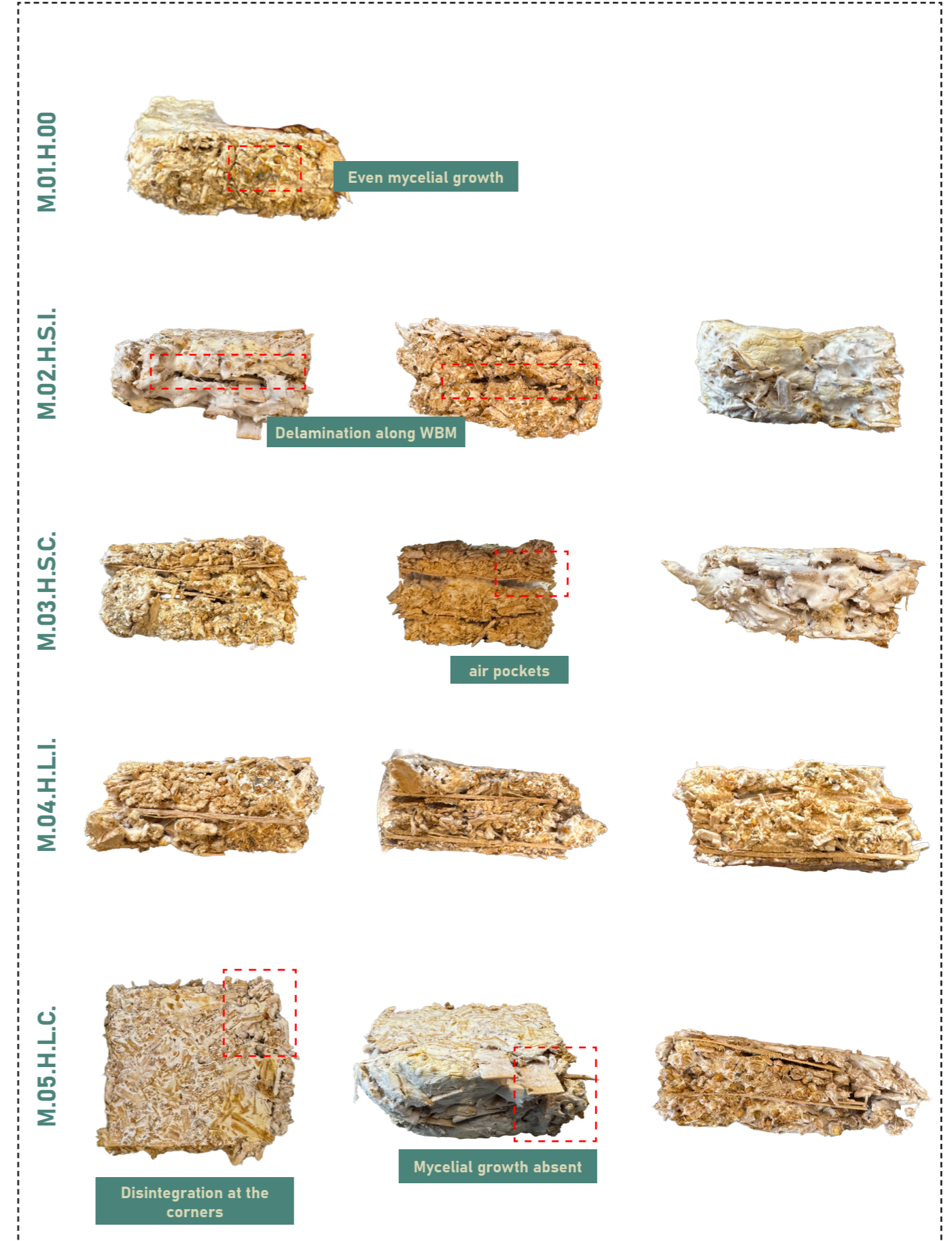


Figure 82: Deformation of the specimens after compression test (Author)

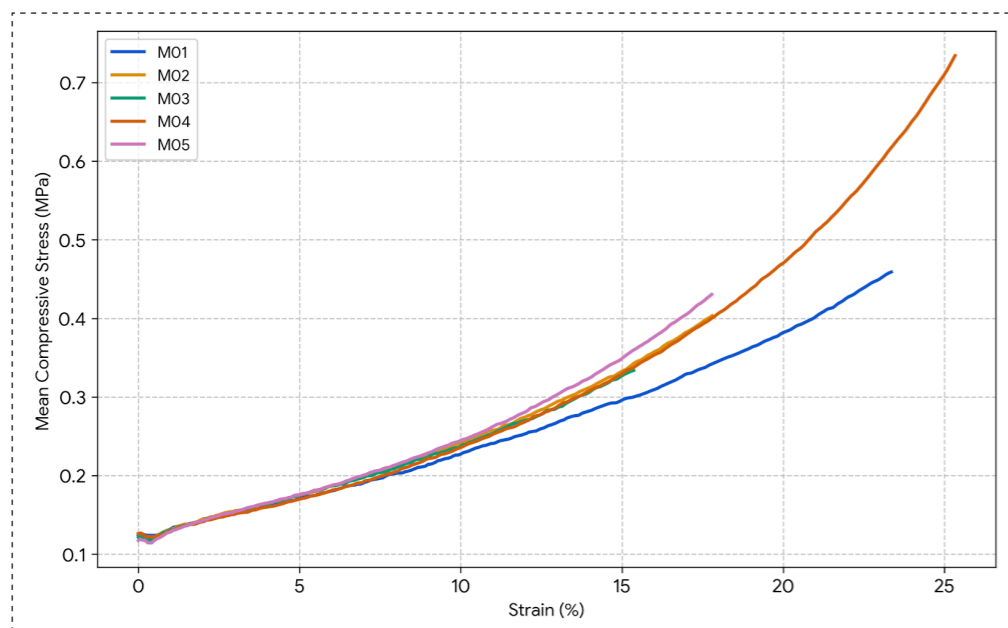


Figure 83: Mean stress-strain curve for all the specimens of Stage 2B (Author)

### Stress-Strain curve:

The stress-strain curves across all specimen groups exhibited characteristic non-linear, elastoplastic behavior, typical of cellular and foam-like bio-composites. Rather than experiencing brittle failure under continuous loading, the specimens demonstrated progressive deformation characterised by distinct strain hardening. This indicates a highly ductile compressive response facilitated by the gradual collapse of the internal cellular macro-pores. As the compressive load increased, the porous mycelial matrix effectively redistributed localised stress concentrations throughout the network, allowing the material to undergo significant internal densification and energy absorption without immediate macroscopic fracture.

Among all specimen groups, the M04 demonstrated superior performance. The stress-strain curve of M04 showed a rapid transition into a pronounced strain-hardening region, reaching peak compressive stresses approaching 1.5 MPa. The steep curve (Fig. 83) indicates enhanced stiffness, improved energy absorption capability and greater resistance to progressive structural collapse. In comparison, the M01, M02, and M03 groups exhibited flatter densification slopes and lower stress development throughout compression, indicating reduced stiffness

and earlier onset of localized yielding. M01 displayed comparatively stable deformation behaviour due to more uniform mycelial colonisation, whereas M02 suffered from premature delamination along the internal layers, resulting in weaker stress transfer and unstable deformation. Similarly, M03 exhibited evidence of internal air voids and incomplete growth, which likely acted as stress concentration sites and reduced the effective load-bearing area during compression. The M05 group exhibited the greatest variability in compressive behaviour, as reflected by the inconsistent stress-strain curves (Appendix 03) and broad yield stress distribution.

### Mechanical performance metrics:

The mechanical data (Table 11) confirms the structural contribution of bamboo reinforcement through clear yield strength differences between the specimen groups. Specimen group M04 achieved the highest mean yield strength of 1.157 MPa, substantially outperforming the small width (5 mm) reinforced specimen groups, which averaged 0.616 MPa. The larger 10 mm grid cell size provided an optimal biological interface. It facilitated better oxygen diffusion during the incubation phase, promoting hyphal colonisation deep within the composite system. Crucially, this specific spatial porosity allowed the actively growing mycelium to physically bridge the gaps and densify. This generated a strong

bonding between the layers making it into a monolithic structural element, severely reducing the risk of delamination under compressive loading. The superior performance of M04 indicates that the large width (10 mm) woven scaffold provided more effective stress redistribution, improved stiffness, and greater resistance to compressive deformation.

The reinforced specimens also showed a major improvement compared to the unreinforced group, M01.H.00, which lacked sufficient structural integrity to consistently maintain its geometry during testing. The increase in load-bearing capacity achieved by M04 demonstrates that the bamboo scaffold functioned as the primary load-bearing framework, while the mycelium mainly contributed to matrix cohesion and densification behaviour. While mycelium contributes essential compressive mass, the 1.157 MPa yield strength of the M04 specimen group demonstrates that a topologically optimized 10mm bamboo woven grid is required to fully activate the composite's potential.

Beyond scaffold geometry, origin type of the material also proved to be a critical factor influencing composite strength. Specimen groups fabricated using Origin Type 02 (India) consistently demonstrated superior mechanical performance compared to

those produced with Origin Type 01 (China). This difference can be primarily to the surface morphology of the bamboo strips. The naturally rough, hand-cut texture of the Indian bamboo created a highly frictional substrate that enhanced mechanical interlocking between the bamboo fibres and the mycelial network. In contrast, the smoother and more industrially processed surface of the Chinese bamboo provided reduced micro-topographical grip for hyphal attachment, resulting in weaker bonding and earlier material separation under compressive loading. These findings indicate that surface roughness and fibre-matrix adhesion play a major role in determining the structural efficiency and load-transfer capability of the composite system.

### Density-Strength correlation

Although the experimental data generally demonstrated a positive correlation between composite density and compressive strength, the M04 specimen group exhibited higher mechanical efficiency relative to its specific mass (Fig. 84). This finding indicates that microstructural optimisation contributes more significantly to strength development than densification alone. Excessive substrate packing or overly dense reinforcement, such as the small width strip (5 mm) weave, likely restricted internal airflow, limiting mycelial colonisation.

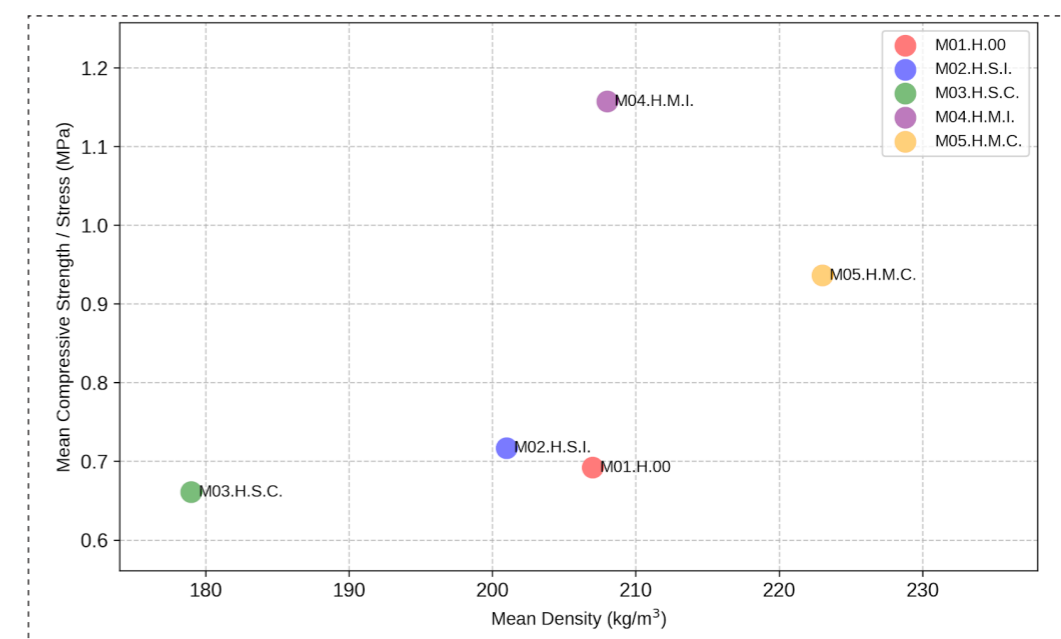


Figure 84: Mean stress vs mean density for all the specimen groups of Stage 2B (Author)

## 11.6 Microscopy test

### Methodology and Objectives

To analyse the interfacial bond between the mycelial matrix and the bamboo reinforcement, high-resolution digital optical microscopy was utilised. Observations were conducted using a Keyence VHX-7000 (Fig. 85) digital microscope, capable of up to 500x magnification with depth composition, located at the Faculty of Architecture and the Built Environment. To ensure the hyphal networks and bonding interfaces remained structurally undisturbed, all tests were performed prior to the compressive testing phase.

The microstructural analysis focused on three primary objectives:

- Evaluating the growth patterns between unreinforced and reinforced composite system.
- Assessing the extent of hyphal growth across layers bridging between stacked bamboo mats
- Observing guided growth behavior along the specific topography of the bamboo fibers.

### Observations

Figure 86 illustrates the unreinforced composite system. The mycelium exhibits scattered, isotropic growth, attempting to randomly colonise the disorganized hemp substrate without distinct boundaries. In contrast, the introduction of the woven bamboo mat actively dictates the biological growth pattern. The physical boundary of the bamboo constrains the hyphae, mitigating random spread and transforming the colonisation into a highly structured, guided network.

Figure 87 demonstrates robust interlayer growth between the internal layers of the woven bamboo. The actively growing mycelium physically bridges the gaps between the mats. This generates a dense,

localised biological ecosystem within the composite's cross-section, establishing the interlock required to prevent delamination under load.

Figure 88 highlights early-stage hyphal development, revealing distinct contact-guided growth. The mycelium preferentially binds to and extends along the longitudinal axis of the bamboo fibers.

These visual data strongly validates the hypothesis: the bamboo reinforcement acts as an active biological scaffold rather than a passive inclusion. It physically guides the mycelial fibers during the incubation phase, cultivating a highly dense, structurally bounded biological composite system that directly enhances the composite's mechanical boundaries.

### Limitations and Future Characterisation

While digital optical microscopy successfully visualises macro-scale hyphal infiltration and general scaffold bonding, this methodology possesses inherent resolution limits. It cannot capture the nanoscale adhesion mechanisms at the individual hyphae level. Due to project time constraints, Scanning Electron Microscopy (SEM) was not conducted. Future research must prioritise SEM imaging to definitively characterise the nanoscale interfacial bonding mechanisms and precisely map the micro-mechanical structural failure modes between the mycelial matrix and the bamboo fibers.

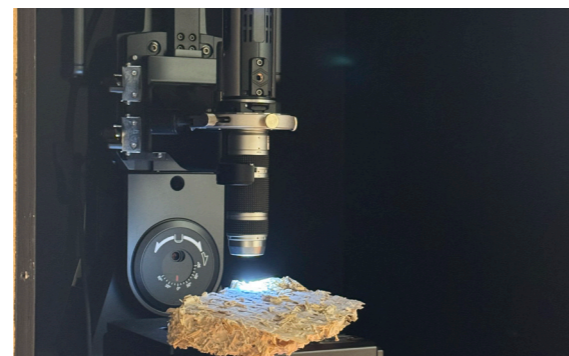


Figure 85: Keyence VHX-7000 digital microscope at the Microscope room at the Faculty of Architecture and the Built Environment (Author)



Figure 86: Growth patterns in unreinforced composite system (Author)

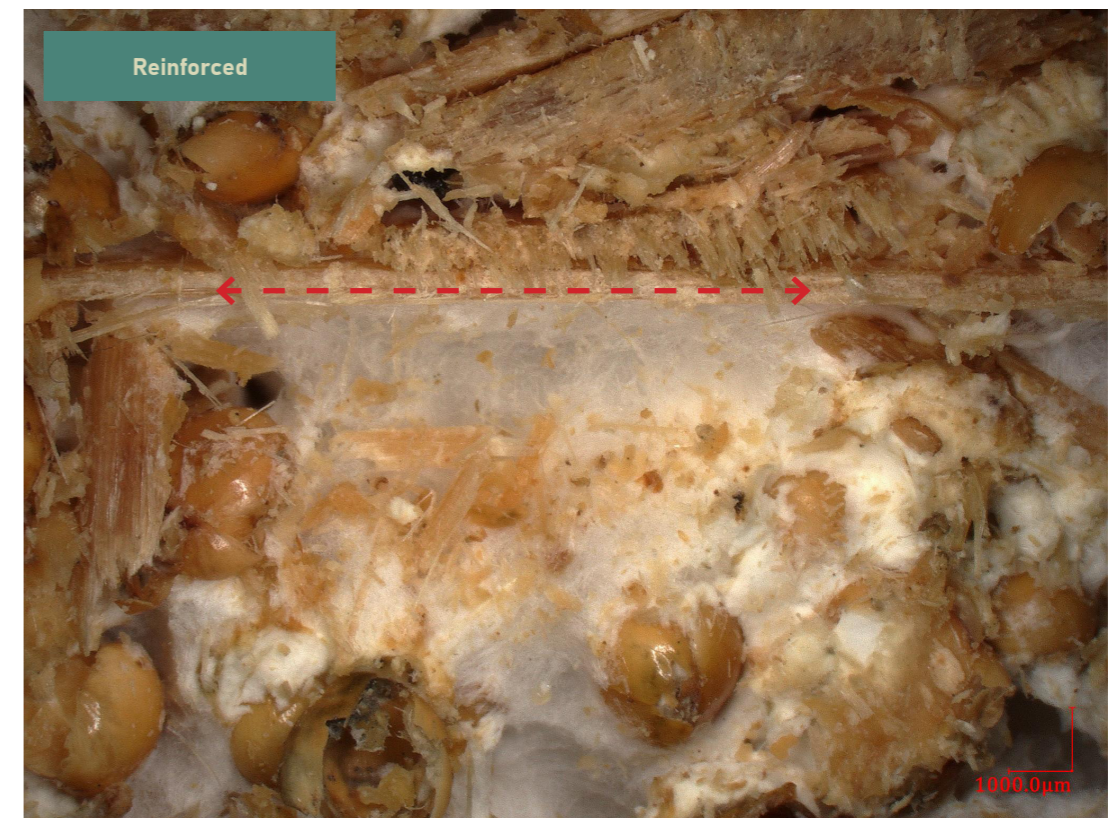


Figure 87: Growth patterns in reinforced composite system (Author)

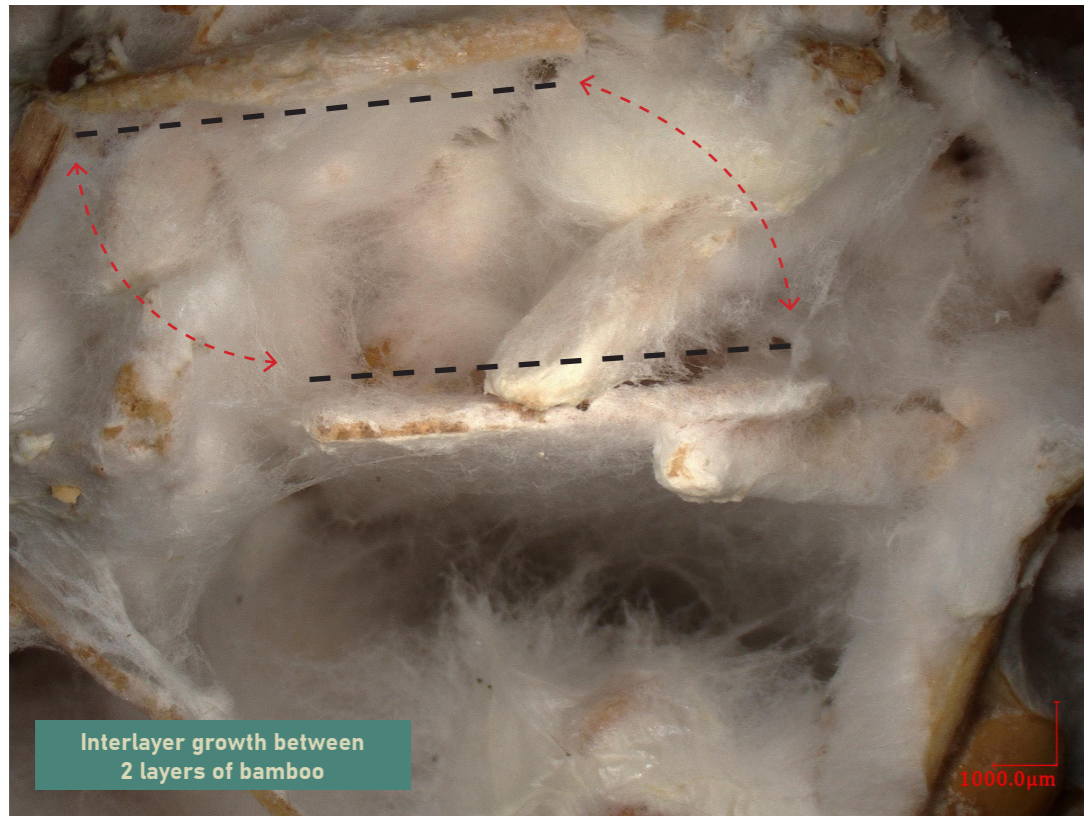


Figure 88: Extent of hyphal growth across layers bridging between stacked bamboo mats (Author)

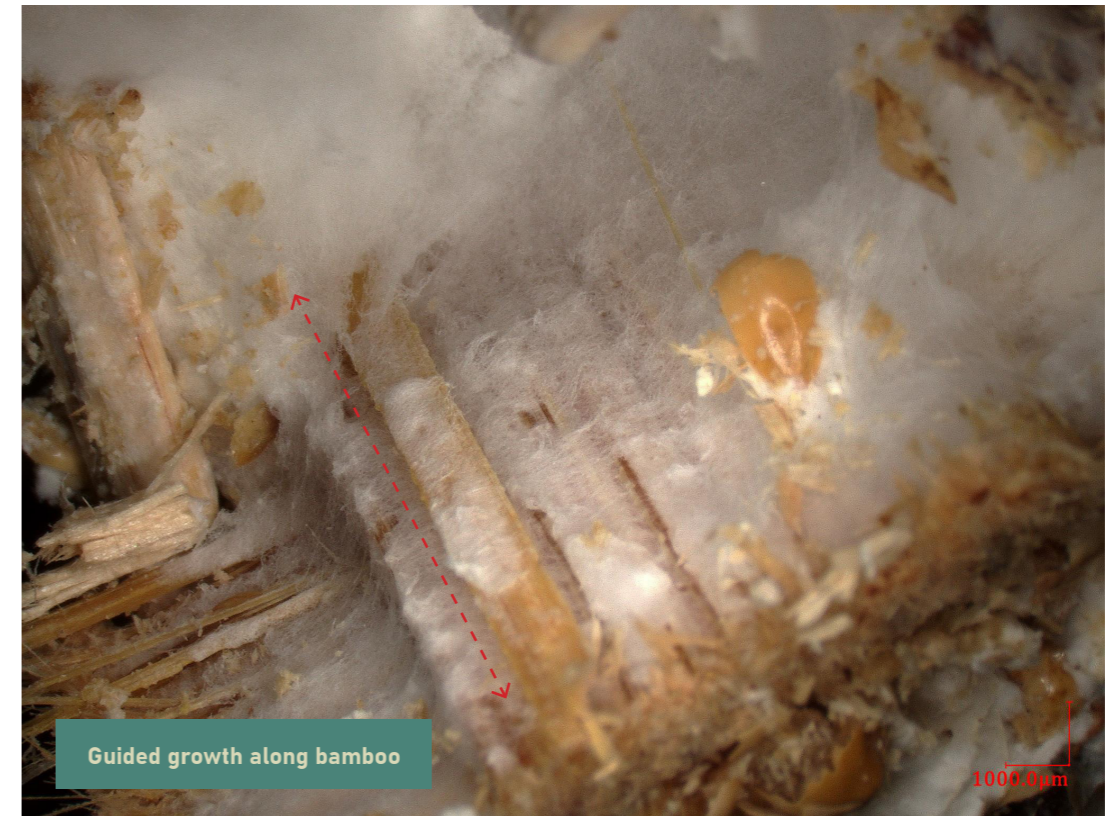


Figure 90: Growth along the bamboo woven matt surfaces (Author)

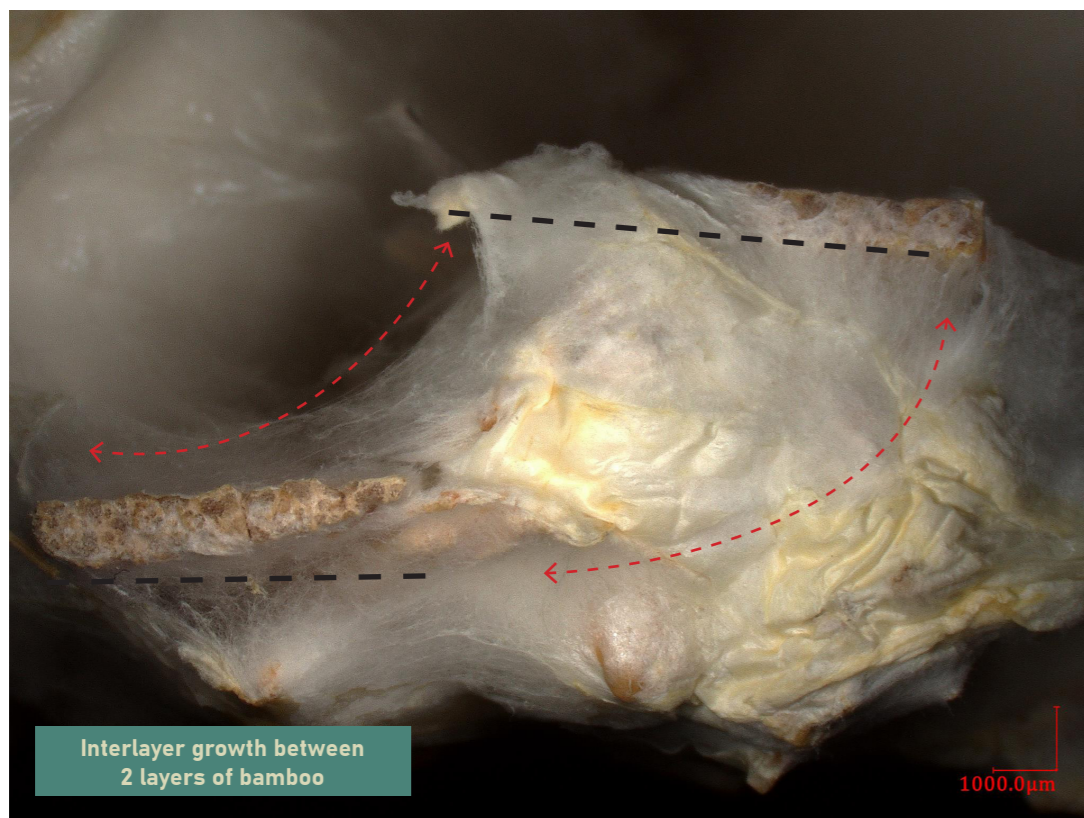


Figure 89: Extent of hyphal growth across layers bridging between stacked bamboo mats (Author)



Figure 91: Growth along the bamboo woven matt surfaces (Author)

## 11.6 Part B Conclusions

Part B primarily focused on establishing fabrication feasibility and observing indicative material behavior. Initially, the research hypothesised that a single, standardised substrate recipe could be immediately applied to the bamboo reinforcement. However, the iterative process revealed that defining and stabilising a fabrication protocol required extensive iterative testing before required structural samples could be cultivated.

The final methodology (Stage 2B & 03) was filtered through a rigorous process of elimination and refinement, directly informed by the logistical and mycelial growth challenges encountered during Stages 00, 01, and 02A. Some of the parameters identified are:

- Maintaining a high volume ratio of mycelium grain spawn to secondary substrate during early inoculation and assembly is critical. A higher initial concentration of mycelium actively overpowers external pathogens, significantly minimizing the risk of contamination.

- Grain spawn proved to be efficient and manageable inoculation medium. However, aligning its procurement and delivery with the exact day of inoculation is necessary to ensure maximum quality of growth.

- The introduction of additives like wheat flour, functions as a highly effective additive, significantly accelerating the rate of initial growth rate.

- Inoculation type 03 (Fig. 93) prioritises the complete colonization of the hemp substrate before integrating the bamboo reinforcement. This ensures the mycelium to dedicate its subsequent growth energy entirely to binding the structural scaffold.

- While high-pressure autoclaves guarantee absolute sterility, these results demonstrate that thermal pasteurisation via boiling water is a viable alternative. This validates

a highly accessible, low-tech preparation method that reduces reliance on specialised laboratory equipment.

- The physical mould setup must balance sealing with oxygen diffusion (Fig. 94). Sealing the moulds with perforated cellophane wrap proved highly effective, retaining necessary internal moisture while permitting essential aerobic circulation.

- The physical handling of the material dictates the final form quality. Densely and uniformly packing the inoculated substrate into the mould is strictly required to achieve a cohesive internal matrix and an even, continuous surface finish. Rightly balanced density (Fig. 92) with porosity giving better results.

Ultimately, Part B confirmed that working with a living biological binder requires active, continuous environmental management. The structural success of the final composite is entirely dependent on rigorously controlling these biological, environmental, and physical variables during the incubation phase.

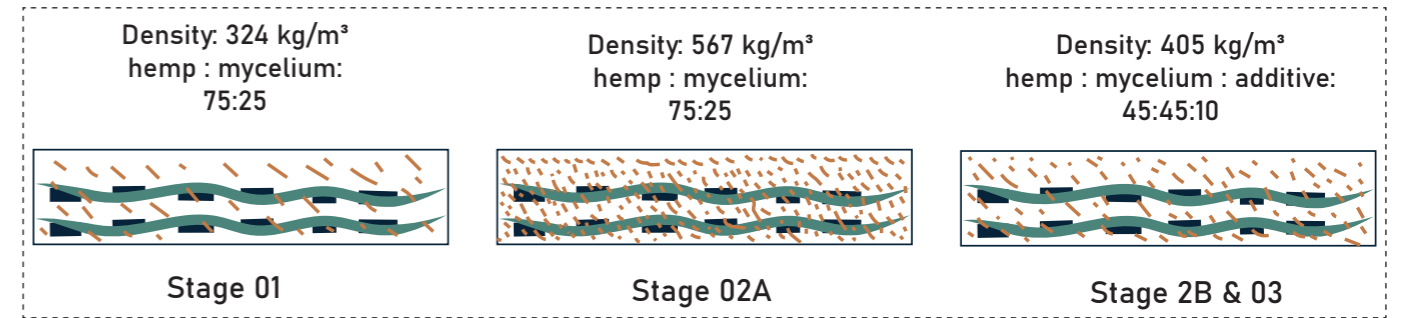


Figure 92: Density & porosity over all the Stages of experiment (Author)

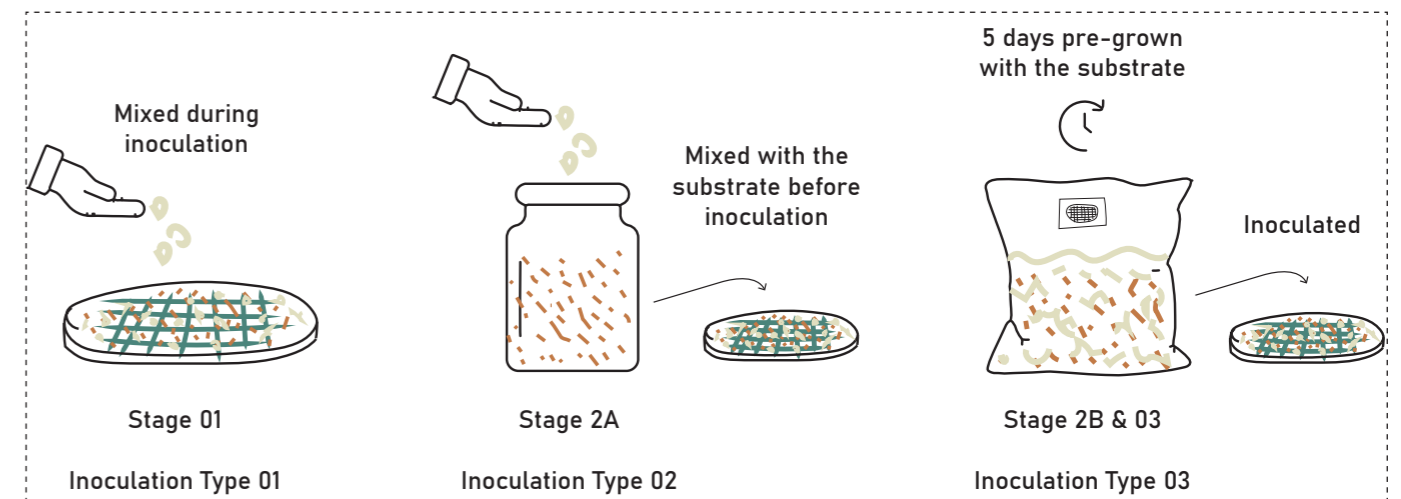


Figure 93: Inoculation types over all the Stages of experiment (Author)

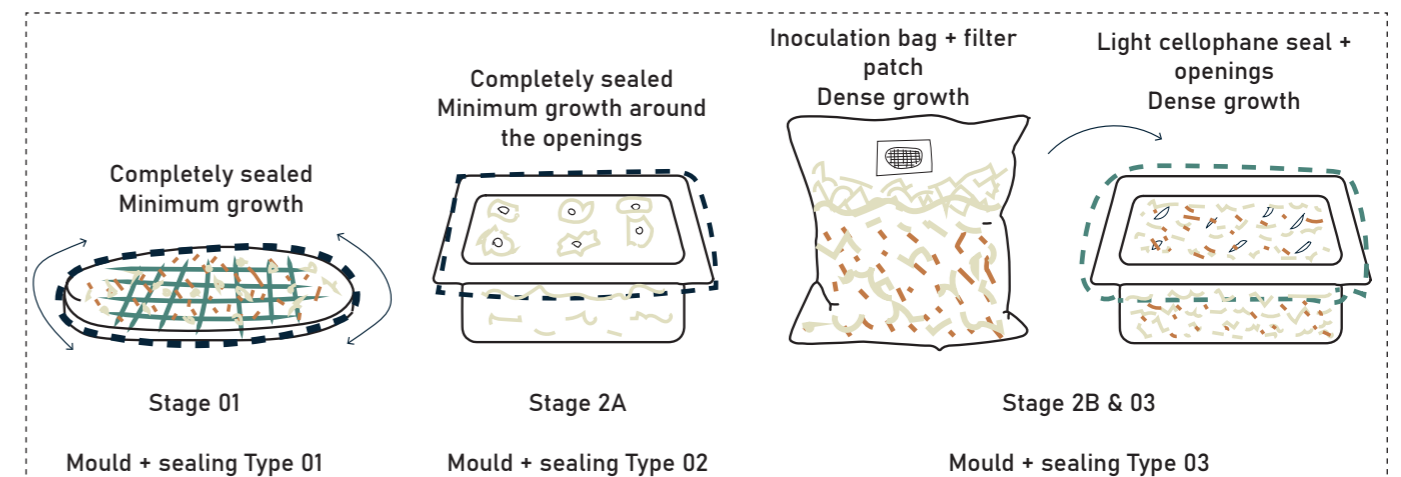


Figure 94: Mould types and sealing for oxygen airflow & avoid risk of contamination (Author)



# PRODUCT DESIGN

Part C

# 12.0

## Material developments

### 12.1 Material system to product

The proposed material system (Fig. 95) was the first stage to exploration of mycelium in combination with WBM. The developed system consisted of two WBM layers filled with mycelium-inoculated hemp substrate, placed between two fibrous layers of mycelium-inoculated hemp substrate to create a section thickness of 50mm.

With the original objective of developing a facade element, the system was well explored as a facade panel and a facade block. This included the intermediate design possibilities with prioritisation to the compressive performance of the material.

Since Stage 01 and Stage 2A did not produce

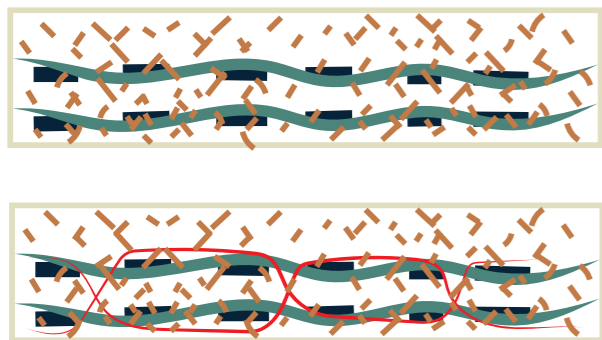


Figure 95: Proposed Material system (Author)

Table 12: Facade product types; pre-requisites for performance (Adapted: De et al, 2025; McGaw et al., 2022)

Product category	Primary role	Key performance requisites
Internal cladding	Interior wall finish	Fire rating, VOC emission limits, impact resistance
Infill wall	Non-load bearing filler (Wind/Dead load)	Wind load resistance, air leakage control, thermal bridging control
Insulation Panel (100mm thick)	Thermal regulation	Thermal resistance, fire resistance
Wall cladding tiles	Weather protective exterior finish	Weather resistance, Water absorption, durability
Low rise Load-bearing blocks	Structural wall and enclosure	Compressive strength, block stability, fire resistance, weather resistance

sufficient results for the material properties, Stage 2B and the product design phase were developed simultaneously.

### 12.2 Pre-requisites for a Facade product

A facade product is required to satisfy several performance criteria, including load-bearing or self supporting capacity, acoustic performance, thermal insulation and compatibility with bio-based sealants for durability. There has been a large emphasis on bio-based materials to enter into mainstream construction which can only be validated through "heirarchical barrier analysis". This specifically addresses the technical gap between current material properties and established building code requirements. (Pacheco-Torgal, 2026).

Existing examples from the mycelium industry have demonstrated applications such as internal cladding, infill walls, insulation panels and wall cladding systems, as discussed in Section 1.1. These applications were considered as potential directions for the proposed material system. Table 12 compares the identified facade applications for their respective key performance requirements.

Although the possibility of the proposed material system MBC functioning as a load-bearing material remained limited, the broader objective was to explore its potential as a building block for low-cost housing, low-rise structures and pavillion scale applications.

### 12.3 Design Parameters

A set of design parameters were established to further boil down the design with the fabrication constraints for the prototype. The composite material system was to be adapted and developed into a feasible architectural building application. A constant thickness of 50mm was maintained throughout the development process, for similar reasons to objectives in Section 9.1. That is to ensure adequate oxygen diffusion for healthy mycelial growth. The system to be explored both as a self-supporting assembly and as a framed structural system.

Additional feasibility factors were also considered during the design process. These included mould-making requirements, limitations related to the prototype dimensions to the size of the incubation fridge and the drying oven. Prototype scale and weaving complexity were also controlled to ensure practical fabrication within the available skill level and time constraints. With respect to woven bamboo reinforcement, maintaining manageable geometries was important for accurate assembly and repeatability.

The available material also influenced the workability and final dimensions of the system. Bamboo from origin type 02 was limited to a constant length of 300mm, while bamboo strips from origin type 01 were a metre long. To maintain consistency and allow comparison between systems, the prototype dimensions were restricted to the 300m length range.

# 13.0

## Form explorations



Figure 97: Rattan furniture (Source: Serena & Lily)

distributing the forces through the section. The mycelium inoculated hemp substrate then acts as a binding matrix around the bamboo reinforcement.

One of the large-scale affordable housing project, (Fig. 96b) Project Phoenix in California, projects also optimised the facade panel through its cross-sectional design. The project developed 38-foot-long (11.5m) prefabricated panels using shredded hemp stalks inoculated with mycelium and enclosed within a fibre-reinforced polymer (FRP) shell.

### 13.2 Bamboo & Rattan furniture

Some precedents from traditional bamboo and rattan furniture fabrication were also accessed and referenced. In particular, the form-finding methods used in rattan chair legs influenced the structural approach of the system. Rather than forcing the material into rigid configurations, the form develops in response to the material's natural structural behaviour. Contemporary design

### 13.1 Extrusion

To start with, the geometrical behaviour of steel structural sections was referred to (Fig. 96a). This is where sectional form and material distribution are used to improve compressive performance and load transfer. The woven bamboo reinforcement helps in

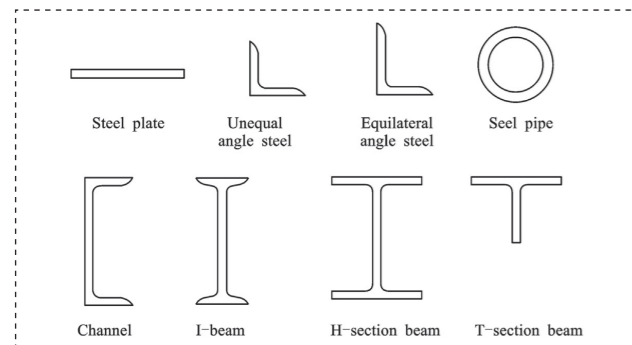


Figure 96a: Cross section types of steel section (Source: Elsevier, 2022)



Figure 96b: (left, middle) Pre-fabricated mycelium based panels (load-bearing) (Author)

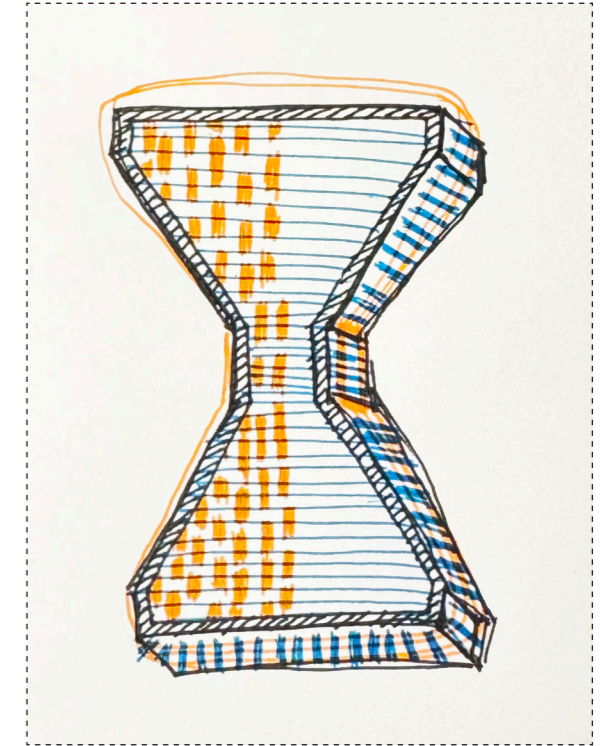


Figure 98: (left) Bombay bhel side table (Source: Tiny Cane Collective); Preliminary sketch design (Author)

applications like the Bombay bhel side table (Fig. 98) from the Tiny Cane Collective was also a precedent referred to. Some structural insights were gathered through discussions with Ritika from team too, through which the preliminary sketch was developed.

### 13.4 Interlocking load-bearing blocks

Analysis from a study indicates a consistent increase in the development of modular components. This trend highlights the critical importance of interlocking, load-bearing blocks. This validates a robust and growing interest in mycelium as a primary construction material. They provide

necessary structural standardisation and reliable assembly logic for larger scales. In contact, monolithic self-supporting systems show moderate development. (Lewandowska et al., 2025)

Tseng et al. (2024) also emphasise the ergonomic importance of modular blocks that can be easily lifted (Fig. 99), handled and assembled by a single person. This improves the accessibility and practicality of the material as a construction product, particularly for self-built, low-cost and small-scale construction projects.

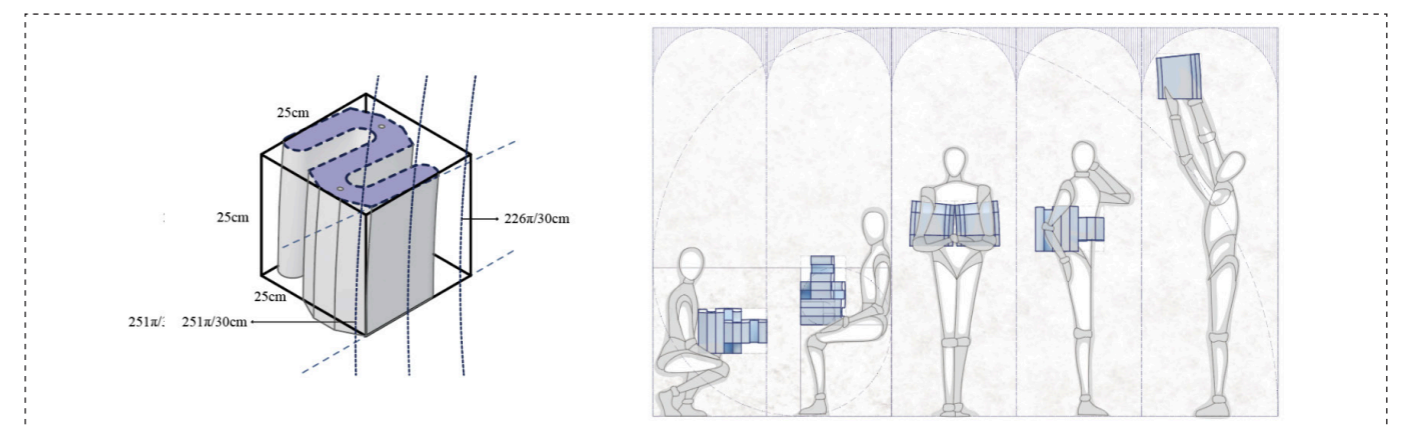


Figure 99: (left) Module design; (right) Module ergonomic analysis (Source: Tseng et al., 2024)

### 13.5 Lightweight and stackable blocks : MycoBlox by Anomalia

MycoBlox is an installation by Anomalia in the MycoMuseum project. A modular wall system (Fig. 100) is developed using mycelium blocks. Developed in collaboration with the Indonesian biotechnology firm MYCL, the units are treated for targeted durability. Indoor blocks receive standard wood coatings, while exterior units utilise natural lime plaster. Structurally, the material exhibits a highly efficient strength-to-weight ratio. An individual block weighs approximately 1.5 to 1.6 kilograms but can withstand up to 1.55 tonnes of compressive load. (Ravenscroft, 2024)



Figure 100: (top right) MycoBlox: Modular Mycelium blocks; (bottom) Wall assembly (Source: Ravenscroft, 2024)

# 14.0

## Design

### 14.1 Interlocking Block Design: Proof of concept

Building upon the insights detailed in Section 13, it was established that the compressive performance MBCs is structurally better optimised within block morphologies. Furthermore, blocks offer significantly higher production feasibility and practical accessibility, particularly within the building industry, where modular, interlocking masonry systems are highly favoured.

To bridge these material findings with architectural application, an interlocking block design was developed as a proof of concept. The base geometry was derived from the dimensions of a standard brick size (Fig. 101). Through a series of extruded and recessed volumetric modifications (push-and-pull mechanisms), the geometry was adapted into an interlocking module capable of bi-directional assembly. Crucially, the maximum thickness of any section of this interlocking block was strictly constrained to 50mm to ensure optimal, continuous mycelial colonisation as established in Section 9.1. The final dimensions were carefully calibrated to remain easily hand-processable at every stage of fabrication, accommodating the size limits of available machinery and the current entry-level scope of the manual bamboo weaving process (as outlined in Section 12).

Stages 01 and 02A could not be completed, the tests suffered from contamination and were ultimately inconclusive for any mechanical characterisation of the material. Therefore, this interlocking block prototype serves primarily as a speculative, forward-looking exploration of how the reinforced composite system can be successfully translated into a scalable product design.

### 14.2 Preparation : Stage 03

Once the block geometry was finalised, selecting an appropriate mould material was critical. Referring from the experimental outcomes of Stages 01 and 2A, the mould required a precise environmental balance: it needed to be sealed adequately to prevent contamination, yet breathable enough to allow sufficient oxygen diffusion for the mycelium to grow. Furthermore, the fabrication process needed a material that could be rapidly assembled in multiple quantities and easily dismantled during the demoulding process.

Given its accessibility to a lot of waste material and ease of workability at the Architecture faculty's wood workshop, 4mm MDF was selected. The panels were cut to size, stuck together and sealed externally with tape to prevent leakages (Fig. 104). MDF is inherently lignocellulosic and would be consumed by the growing mycelium, the interior surfaces of the mould were completely lined with plastic cellophane tape, creating an impermeable barrier between the substrate and the mould walls. The substrate recipe and inoculation protocol remained identical to those detailed in Stage 2A, with adjustments made solely to the physical assembly method within the mould.

### 14.3 Assembly

As illustrated in Figure 108, the composition of the block required the precise insertion of WBM's at strategic structural locations. To ensure robust binding, the mats were evenly distributed within the continuous,

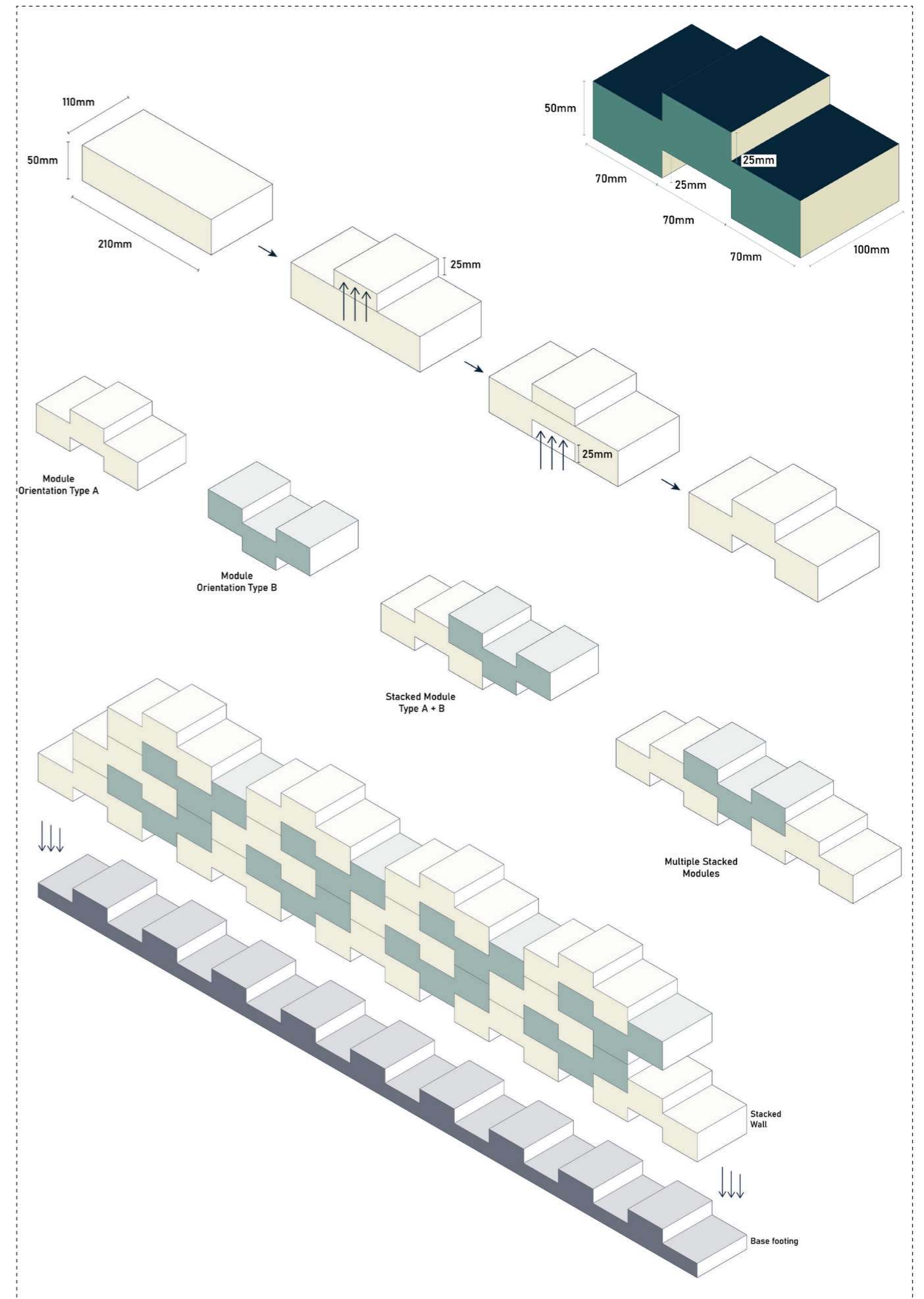


Figure 101: Evolution design of the interlocking block design (Author)

staggered 50mm profile. Specifically, every 50mm section of the block received two WBMs placed adjacently. As demonstrated in earlier Stage 2A tests, this dual configuration facilitates excellent compaction and allows the mycelium to effectively bind the substrate into a unified structural composite system.

Following inoculation, the assemblies were incubated at a continuous humidity of at least 50% and an average temperature of 24°C–26°C. While the internal plastic cellophane lining helped in a smooth demoulding process, the resulting exterior surface finish of the blocks was visually uneven and lacked aesthetic finish. This irregularity was primarily caused by localised clumping of the inoculated hemp. Additionally, a deliberate effort to avoid over-packing the mould, given the history in Stage 2A, which can suffocate the mycelium by eliminating air gaps. It resulted in a looser substrate distribution that created unwanted surface voids.

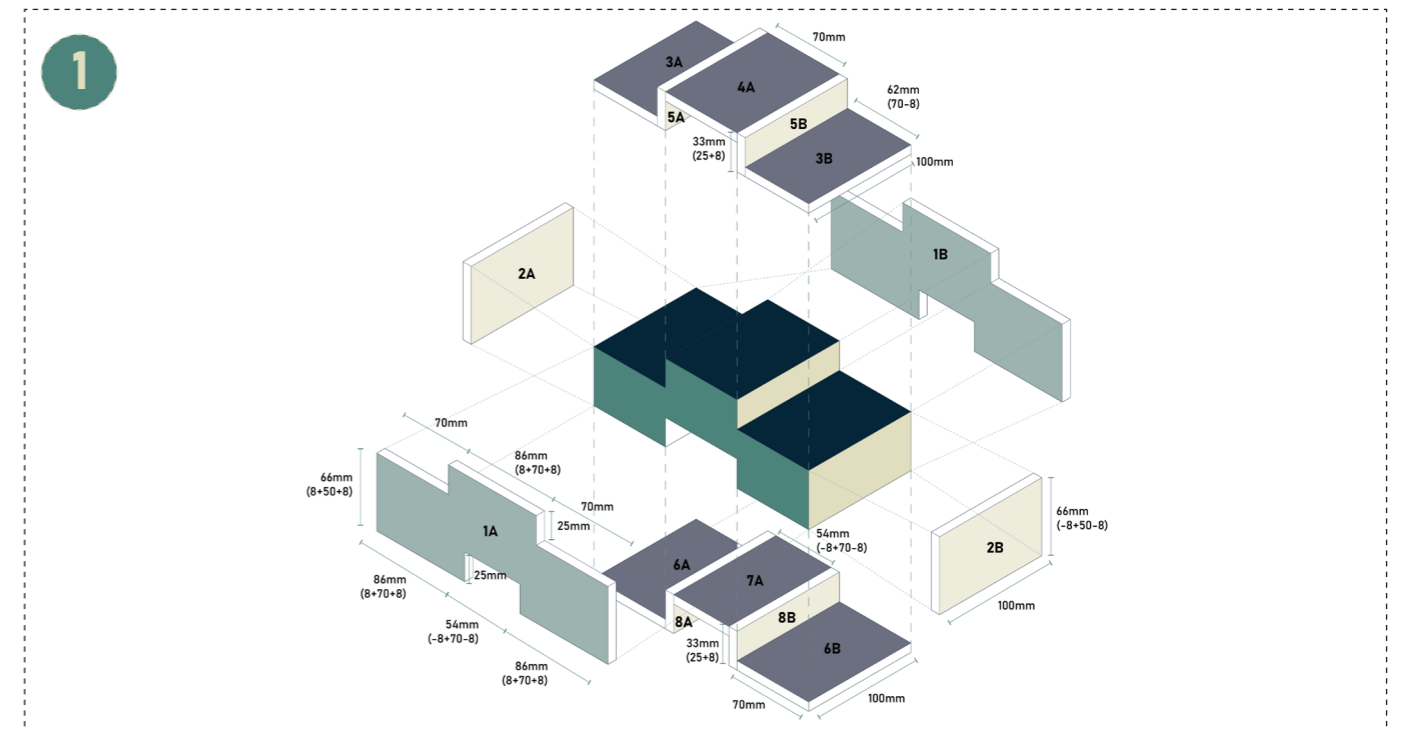
Due to material availability constraints and the diversion of substrate required to revive Stage 2B, the specimen series of Stage 03 only used narrow 5mm wide bamboo strips, limiting the cell size of the grid. A total of five test specimens were fabricated for this proof of concept:

- M06 & M07: Bamboo Origin Type 02
- M08 & M09: Bamboo Origin Type 01
- M10: Unreinforced control block (hemp substrate only)

Following the thermal deactivation cycle, the blocks exhibited an average water weight loss of approximately 50%. Notably, this mass reduction was more than in the Stage 2B specimens, despite having the same thermal deactivation protocol. This accelerated drying rate can likely be because of the block's staggered interlocking profile, which significantly increases the exposed surface area as well as the slightly looser spatial porosity of the packed substrate.

**Table 13: Water mass loss during deactivation: Stage 03 (Author)**

Sample	Before (g)	After (g)	Mass Lost (g)	% Lost
M10.H.00	254	153	101 g	39.80%
M08.S.C.A.	254	122	132 g	52.00%
M06.S.I.A	271	115	156 g	57.60%
M09.S.C.B	410	190	300 g	61.20%
M07.S.I.B	393	180	213 g	54.20%



**Figure 102: Evolution design of the interlocking block design (Author)**



**Figure 103: Use of MDF for creating the mould (Author)**



**Figure 104: Assembly of the mould (Author)**

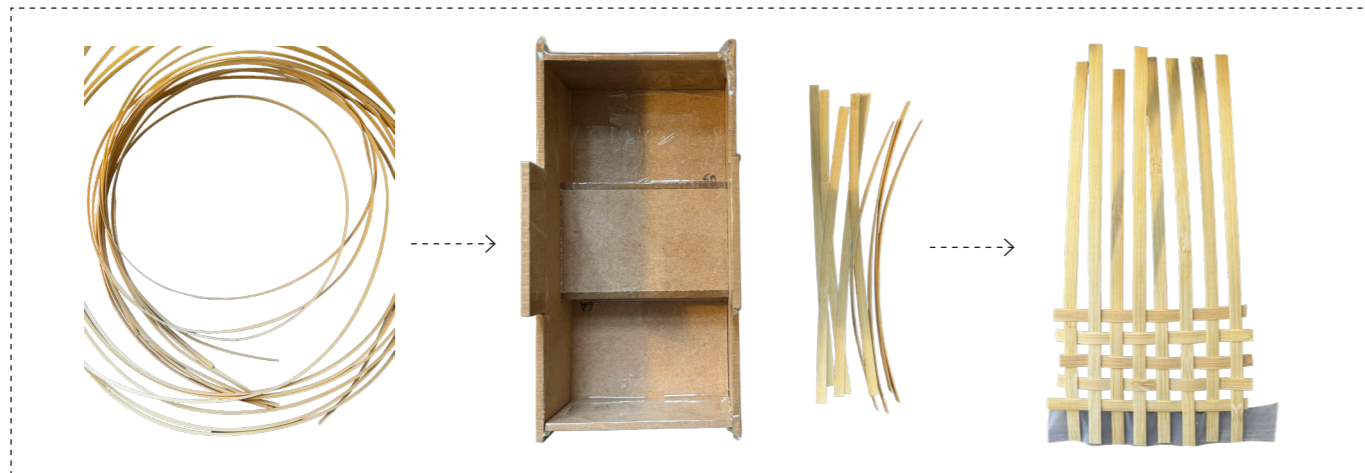


Figure 105: Bamboo weaving in WBM for the proposed mould (Author)

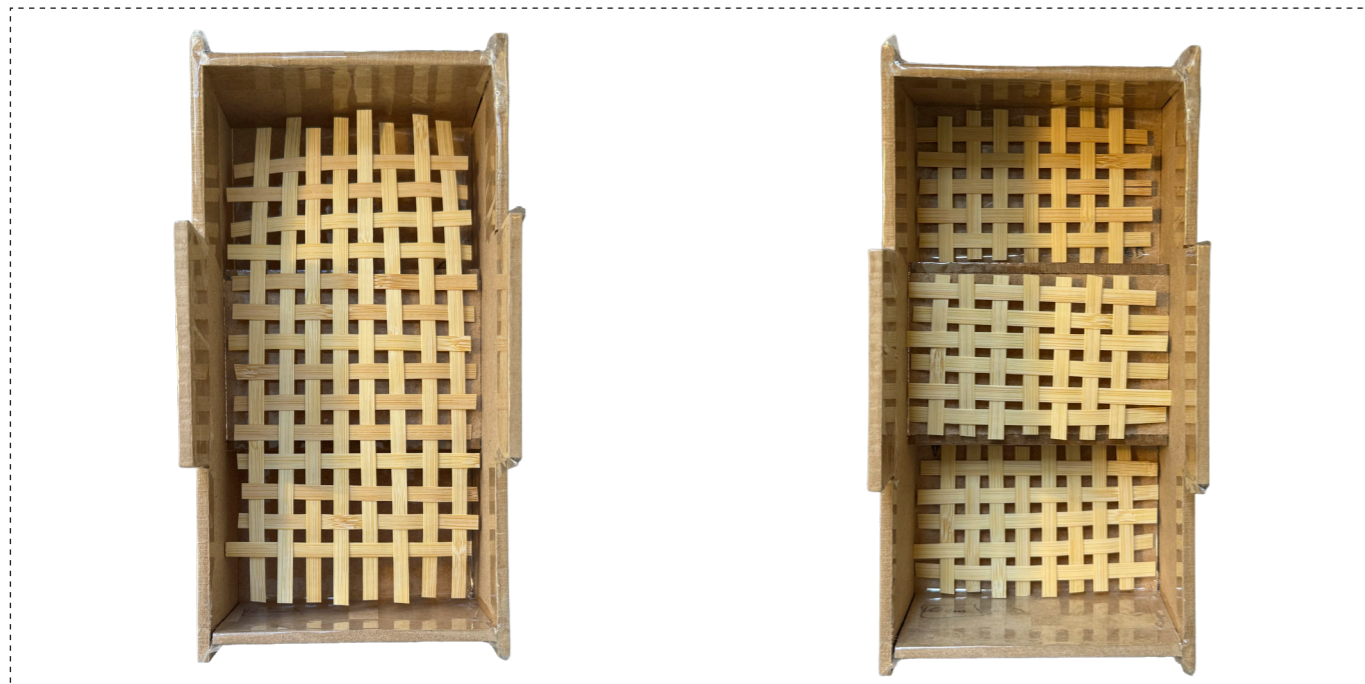


Figure 106: (left) WBM placed in the mould; (right) Smaller WBM placed in the mould in accomodate the stagger (Author)

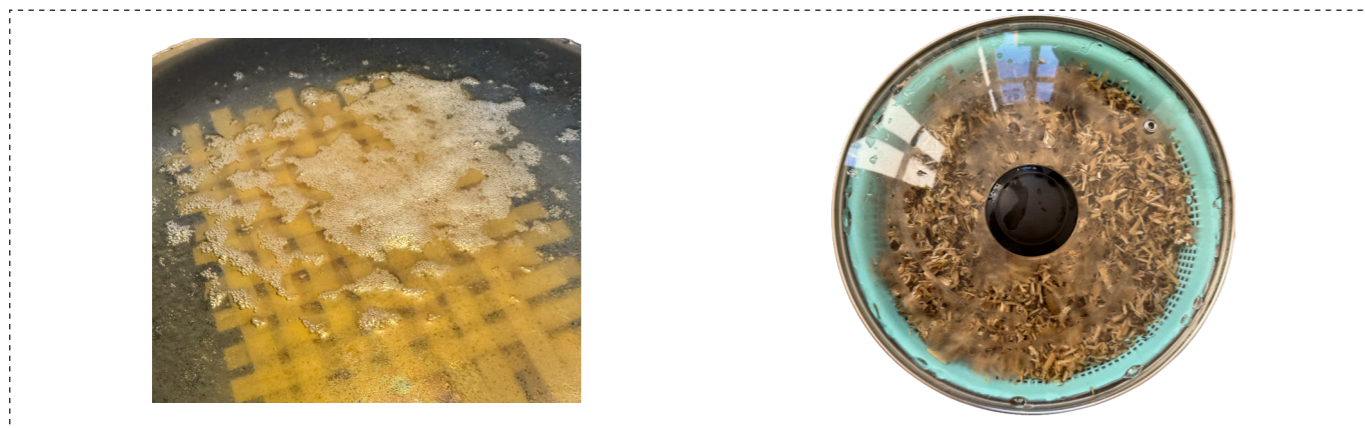


Figure 107: (left) Sterilisation of WBM by soaking in boiling water; (right) Sterilisation of Hemp by soaking in boiling water (Author)

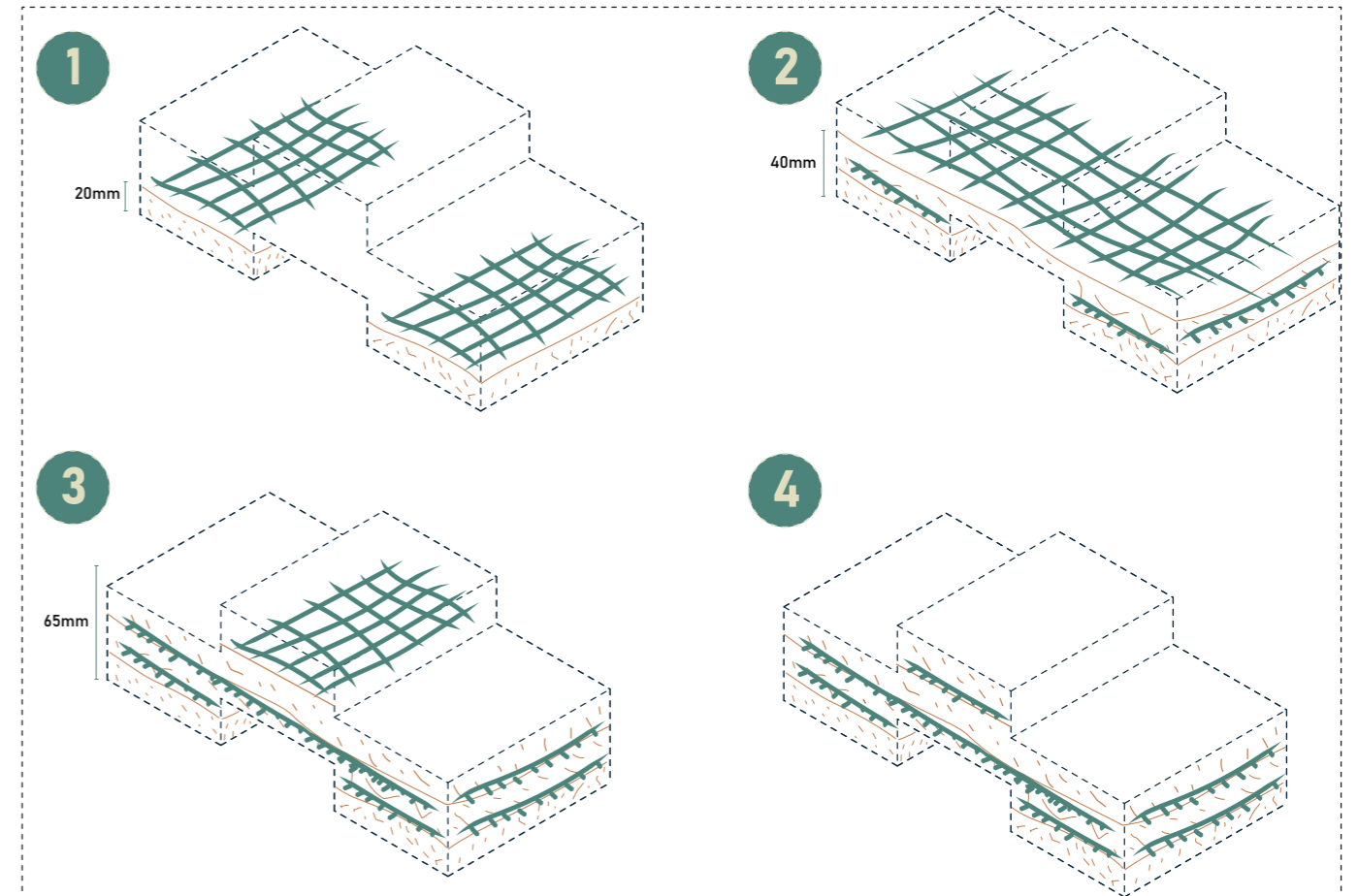


Figure 108: Stage 03: Assembly Sequence (Author)



Figure 109: Stage 03: (left) Incubation, Humidity & temperature tracking; (right) After demoulding, before thermal deactivation (Author)



Figure 110: M07.S.I.B: (left) After demoulding, before thermal deactivation; (right) After thermal deactivation (Author)

## 14.4 Compression test

During the demoulding phase, the unreinforced specimen composed exclusively of hemp (M10.H.00) suffered a critical split along its staggered leg, therefore structurally unsuitable for testing. Consequently, the four bamboo-reinforced specimens progressed to the mechanical testing phase. Due to the current absence of standardised testing protocols specifically for interlocking mycelium bio-composites, compressive strength was tested following the ASTM D1621 (Standard Test Method for Compressive Properties of Rigid Cellular Plastics). Interlocking gaps were filled to create a flush, parallel surface area, ensuring even load distribution across the block's cross-section. Due to fabrication time constraints, a provisional solution was executed wherein mycelium blocks were cultivated specifically to act as filler material (Fig. 111) within these gaps during the test setup, which were also reinforced with bamboo.

## 14.5 Results and observations

Early observations prior to testing revealed several geometric and structural defects across the specimens. Due to the manual

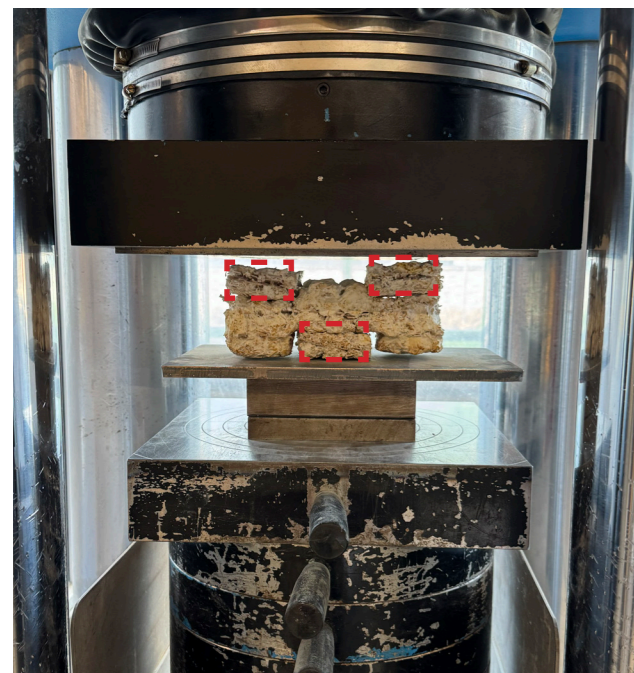


Figure 111: Specimen M07.S.I.B.(left) before and (right) after the compression test( (Source: Author)

packing of the molds, some blocks exhibited misalignment and poor form definition. Furthermore, the provisional mycelium filler blocks did not achieve the required dimensional precision to evenly fill the interlocking gaps, potentially introducing localised stress concentrations during the application of the compressive load. Following the thermal deactivation cycle, the specimens resulted a weight loss profile that differed significantly from the earlier Stage 2B samples even though they were part of the same cycle.

Structurally, early signs of failure were visible in certain blocks even before the load was applied. For instance, specimen M09.S.C.B (Small width 5mm, China origin type 01) exhibited prior delamination at the leg and incomplete mycelial growth. This poor bonding reflected directly with mechanical performance, as M09.S.C.B recorded the lowest yield strength in the batch at 0.489 MPa. In contrast, specimen M07.S.I.B (Small width 5mm, India origin type 02), which remained completely intact and more densely packed, achieved the highest yield strength among the Stage 3 blocks at 0.72 MPa, with a mean compressive strength of 0.616 MPa.

Additionally, survivor specimens from the



Table 14: Compression test results from Stage 03 & Stage 2A (Source: Author)

Stage	Specimen type	Deformation (mm)	Fmax (kN)	Yield strength (MPa)	Mean Compressive strength (MPa)	Density [kg/m <sup>3</sup> ]	Conditions before the test (limitations)
Stage 3 <i>Staggered Specimen dimensions : 190mm x 90mm x 65mm</i>	M06.S.I.A <i>(Small width 5mm, India origin type 02)</i>	22.303	8.74	0.511	0.616	138	early signs of delamination and incomplete growth
	M07.S.I.B <i>(Small width 5mm, India origin type 02)</i>	24.303	12.31	0.72		110	completely intact and more densely packed
	M08.S.C.A. <i>(Small width 5mm, China origin type 01)</i>	22.223	10.96	0.641		103	signs of incomplete growth around bamboo mat
	M09.S.C.B <i>(Small width 5mm, China origin type 01)</i>	20.481	8.36	0.489		171	delaminated at the leg; incomplete growth
	M10.H.00 <i>(Only hemp; no bamboo)</i>	-	-	-		162	Split at the leg; unsuitable for testing
Stage 2A <i>Specimen dimensions: 180mm x 120mm x 40mm</i>	L.J.I.6B <i>(large, joined, India origin type 02)</i>	19.654	18.21	0.843	0.698	-	survivor; minimum growth (refer image)
	L.J.I.6A <i>(large, joined, India origin type 02)</i>	15.727	11.92	0.552		-	survivor; very little growth (refer image)

Stage 2A batch (L.J.I.6A and L.J.I.6B) were tested as standardised brick forms. These specimens featured large, joined bamboo mats but exhibited very little mycelial growth due to the conditions of the Stage 2A. Despite enduring a harsh cultivation environment, specimen L.J.I.6B demonstrated remarkable resilience, recording a peak yield strength of 0.843 MPa and sustaining a maximum force (Fmax) of 3.794 kN. This indicates and further validates that the structural integrity provided by the larger, joined bamboo reinforcement grid proves to be superior to the small width in performance of mycelial bonding and therefore also in the yield strength. It can partially compensate for poor mycelial colonization in the surrounding substrate.

## 14.6 Key takeaways

Moisture and Porosity: The difference in

weight loss compared to Stage 2B can likely be due to the looser porosity of the packed substrate and the increased surface area because of the staggered interlocking form, which sped up the drying process.

Substrate compaction: Manual packing is insufficient for standardised structural applications. Tighter compaction is required to avoid unwanted voids. Future iterations would benefit significantly from cold-pressing techniques to increase material density, enhance fiber-to-mycelium bonding, and yield better mechanical results.

Additives: The addition of wheat flour to the substrate mix proved highly beneficial for stimulating robust mycelial growth as the growth was faster and better within 8 days' time and should remain a standardised step in the inoculation protocol.

Refined testing methodology: The testing

setup for interlocking geometries requires greater precision. Future compression tests must utilise exact, rigid inserts (such as custom-machined metal fillers) rather than organic fillers to ensure perfectly parallel loading surfaces and eliminate stress concentrations caused by uneven gaps.

**Geometric Optimisation:** To mitigate delamination and stress at sharp geometric transitions (such as the interlocking legs), future block designs should explore more curved, filleted forms to distribute compressive loads more smoothly.

**Unified mat integration:** To prevent the composite from behaving as separate laminated layers, joining with strip ties must be established between the woven bamboo mats prior to inoculation, ensuring the entire block grows and functions in unison.



Figure 112: Survivor specimen after compression test from Stage 2A: L.J.I.6A (left) front side (right) backside (Author)



Figure 113: Stage 03: M08.S.C.A Specimen disintegration after compression test (Author)



Figure 114: Stage 03: M06.S.I.A Specimen with delamination at both the legs of the specimen; After compression test (Author)

# 15.0

## Application

### 15.1 Potential applications

Building upon the foundational applications of mycelium in packaging and internal acoustic partitioning established in Section 1.1, the enhanced mechanical properties of the bamboo-reinforced composite validate its viability for structural architectural implementation. The applications and joinery schematics detailed herein represent preliminary proof-of-concept models requiring further structural validation.

The interlocking geometry of the block system provides a highly scalable solution

for low-cost construction. As illustrated in figure 117, which details a typical wall section, MycoMax interlocking blocks can be deployed as load-bearing or exterior cladding elements. The decentralized fabrication model inherently democratizes the construction process, enabling localised assembly of makeshift or permanent structures without heavy machinery.

Introducing MBCs into high-visibility public architecture is critical for normalising bio-based material palettes. Figure 116 presents an AI-generated conceptual adaptation based on the Belgian Pavilion at the 18th International Architecture Exhibition (La Biennale di Venezia), demonstrating the material's spatial and aesthetic potential within a public-facing cultural context.

The compressive yield capacity of the bamboo-reinforced MBC allows for experimental use in public furniture. Figure 115 illustrates the application of MycoMax in a coffee table assembly, highlighting the structural viability of "bio-welding." This technique utilises the living mycelial network to organically join adjacent blocks prior to thermal deactivation, yielding a monolithic biological bond that eliminates the need for synthetic adhesives.

For demountable or temporary architectural

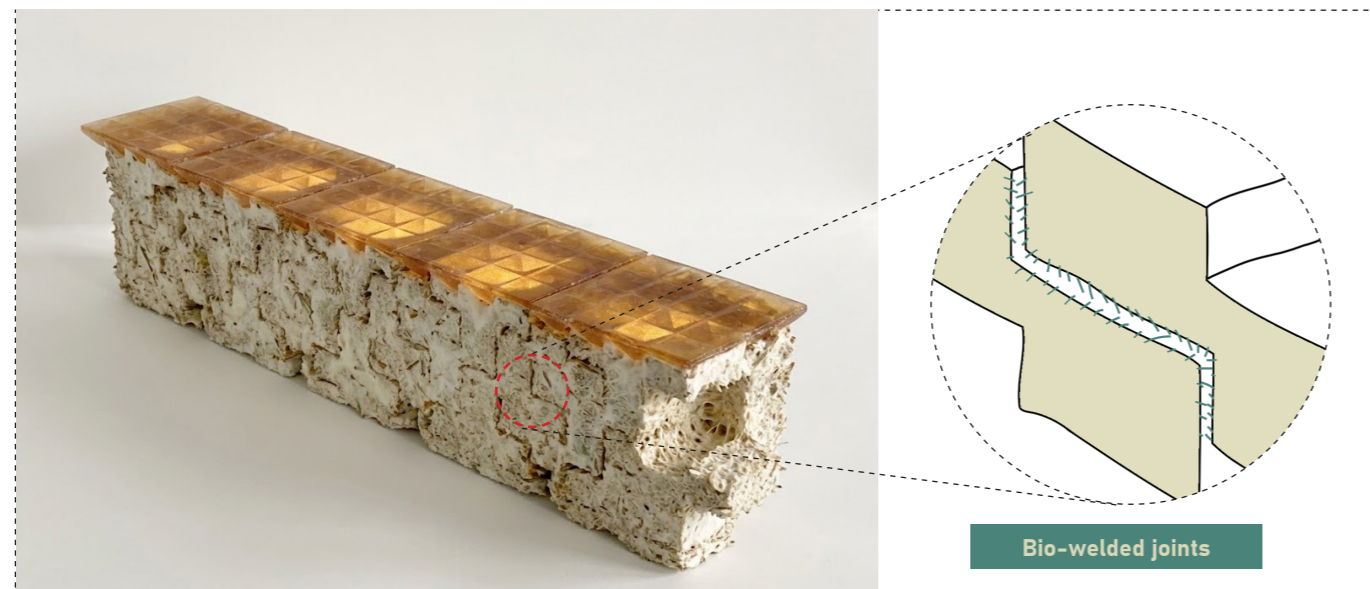


Figure 115: AI-generated interpretation of a MycoMax block coffee table design assembled with the help of bio-welding joints (Author)



Figure 116: AI-generated interpretation based on the Belgian Pavilion at the 18th International Architecture Exhibition – La Biennale di Venezia (Author)

applications, the composite blocks can be integrated into secondary structural wooden frames and secured utilising traditional wooden peg joinery.

### 15.2 Product finishes

To transition MBCs from a laboratory-scale prototype to a commercially viable building material, critical performance metrics and surface treatments must be optimised.

To mitigate the inherent hydrophilicity of the composite system, exterior applications require the application of bio-based sealants. These surface treatments provide essential moisture resistance and enhance the composite's longevity without compromising its end-of-life biodegradability.

MBCs demonstrate intrinsic fire-retardant properties derived directly from their biological composition. The fungal cell walls consist primarily of chitin, a natural

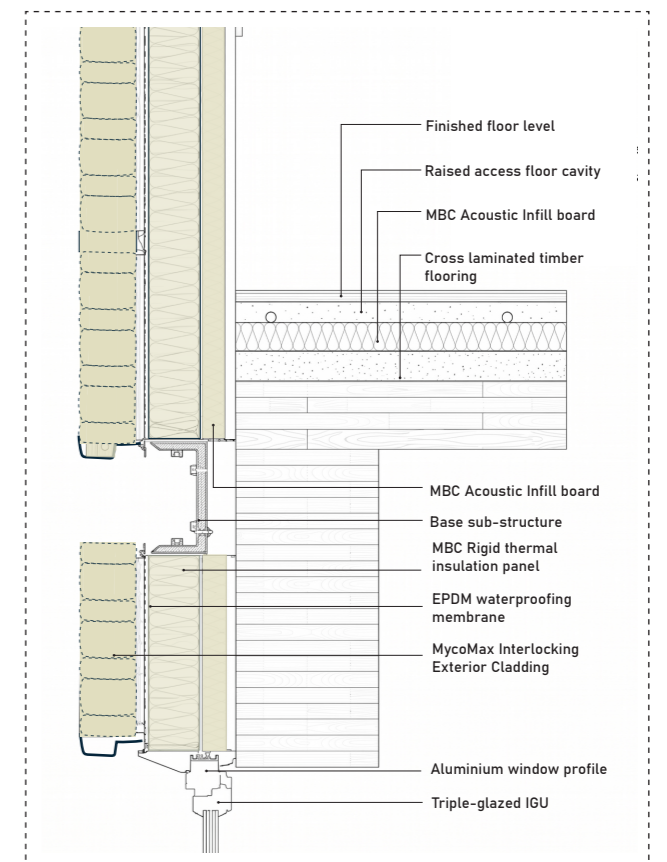


Figure 117: Typical wall section illustrating MycoMax: Cladding material help of bio-welding joints (Author)

biopolymer that functions as an effective thermal barrier. Upon exposure to direct flame, the composite undergoes pyrolysis rather than melting, forming a carbonised char layer that insulates the underlying matrix and prevents the release of toxic volatile organic compounds (VOCs). Existing literature confirms that MBCs exhibit superior fire safety compared to synthetic insulation (such as polystyrene), characterised by self-extinguishing behaviors and significantly lower heat release rates (Jones et al., 2018).

Additionally, Low-density infill MBCs report thermal conductivity values between 0.057 and 0.066 W/mK, firmly satisfying the standard regulatory threshold for thermal insulation ( $\leq 0.07$  W/mK) (Bitting et al., 2022). Additionally, the highly porous cellular macro-structure yields excellent normal sound absorption coefficients, validating its use in acoustic partitioning discussed in Section 1.2.

### 15.3 Accessibility

A primary advantage of the proposed material system is its low barrier to entry. The production of bamboo-reinforced MBCs does not inherently require heavy industrial equipment or highly capitalised factory infrastructure, making the process highly accessible.

To scale the system from laboratory production to community or industrial application, several logistical optimisations can be proceeded with for improved accessibility. The highly energy-intensive process of strict thermal sterilisation can be effectively replaced with bulk pasteurisation for the agricultural substrates. This drastically reduces energy consumption while maintaining sufficient biological control for the target fungal strain. Mycelium can be reproduced easily. Once a primary grain spawn is procured, it can be continuously multiplied using the same localised setup, eliminating reliance on external biological suppliers.

The primary volumetric mass of the composite relies on agricultural waste (hemp shives). This residue is generated actively and abundantly by existing agricultural sectors, the raw material supply chain remains highly accessible, low-cost and non-extractive.

## 15.4 Proof of Sustainability

### 15.4.1. Introduction

The sustainability performance of the proposed block design is evaluated based on the methodology of procuring data from Environmental Product Declaration (EPD). EPD is a third-party verified document over the environmental impact of a product based on Life Cycle Assessment (LCA). Owing to the limited availability of EPDs of MBCs and to ensure reliable and comparable data, all the quantitative data was directly derived from published literature with similar LCA methodologies and standard datasets from the ecoinvent database. The study aims to compare the proposed block design to a conventional concrete infill block and insulation material like EPS. To quantify the effect of suggested interventions on the overall environmental footprint, lab-scale LCA scenarios for A1-A3 stages were developed. Refer to Appendix 5 for complete breakdown of the calculations.

### 15.4.2. Scenario A: Life Cycle Assessment (A1-A3)

The “production cradle to gate” emissions Table 15 were interpreted as approximately equivalent to GWP-fossil. The CO<sub>2</sub> storage was interpreted as GWP-biogenic excluding end-of-life.

#### A1: Raw material supply

The analysis considers the specific bamboo

Table 15: Scenario A: LCA analysis of the proposed product design for A1-A3 stages with improved Scenario B; Cradle to Gate; Appendix 5 for complete breakdown (Author)

PRODUCT STAGE : Cradle to Gate						
		Unit	A1: Raw material supply	A2: Transport	A3: Manufacturing	A1-A3 total
	(components of each process)	all the results are per m <sup>3</sup> production	(Growing + cultivation + processing) Mycelium, Bamboo, Hemp	China -> NL India -> NL Rotterdam -> Delft	Boiling + Autoclave + Inoculation + Incubation + Heat inactivation	
Scenario A	GWP-fossil	kg Co <sub>2</sub> e/m <sup>3</sup>	275.6	47	94.55	417.15
	GWP-Biogenic	kg Co <sub>2</sub> e/m <sup>3</sup>	-477	0	0	-477
	Net GWP-total	kg Co <sub>2</sub> e/m <sup>3</sup>	-201.4	47	94.55	-59.85
Scenario B	Net GWP-total	kg Co <sub>2</sub> e/m <sup>3</sup>	-201.4	5	50	-146.4

reinforcement utilised in the prototype (Origin Type 02). Given the current lack of industry-standard Environmental Product Declarations (EPDs) for hand-cut bamboo, GWP values were derived from established LCA methodologies developed by INBAR (Vogtlander & van der Lugt, 2015). For the cultivation of *Pleurotus ostreatus* (oyster mushroom) grain spawn, data was derived from Rotterzwam (2023), which reports an avoidance factor of 5.4 kg CO<sub>2</sub>e per kg of mushroom produced. Furthermore, the GWP for industrial hemp shives was adopted from 2024 benchmarks, accounting for a cradle-to-gate impact of -1.29 kg CO<sub>2</sub>e per kg, reflecting its significant carbon-sequestration capacity.

The LCA calculations are based on the volumetric composition per m<sup>3</sup> of the structural composite, defined by the following mass ratio:

- Mycelium grain spawn: 40%
- Chopped Hemp shives: 50%
- Woven Bamboo Mat: 10%

All values account for the cumulative impacts of cultivation, growth, and primary processing. Minor material inputs, including the 4mm MDF mold components and the adhesive tapes, were assumed to have a negligible contribution to the total GWP and were therefore excluded from this analysis.

#### A2: Transport

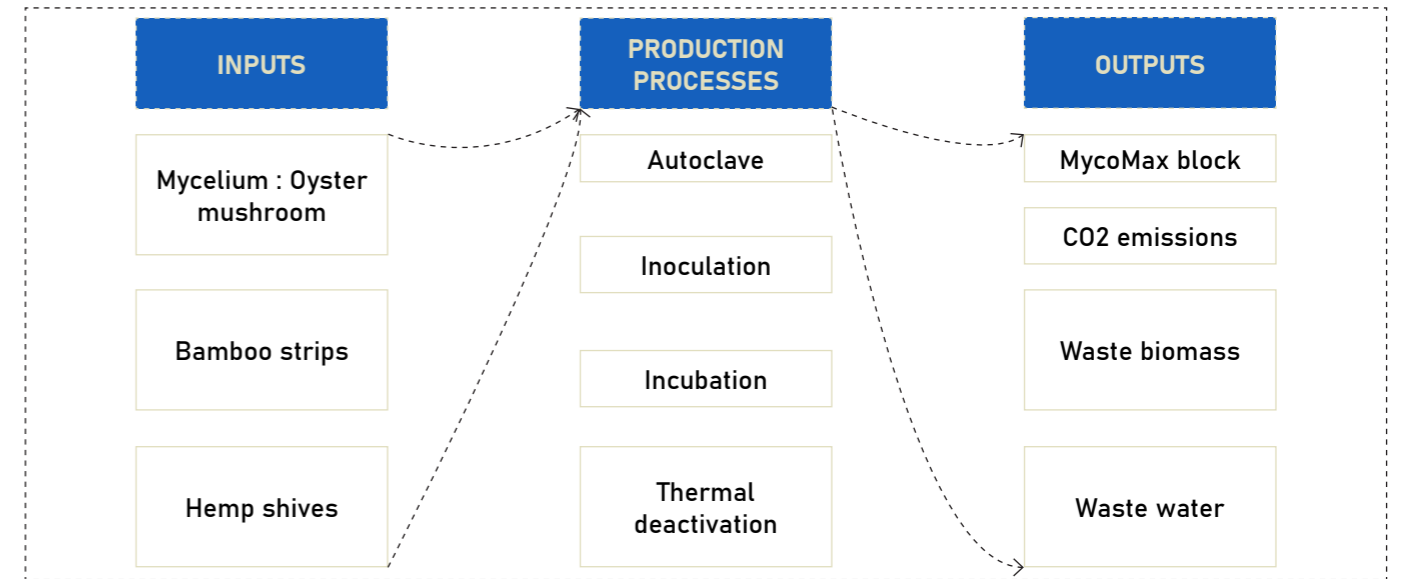


Figure 118: Production inputs and outputs of energy (Author)

Table 16: Scenario A: LCA analysis of the proposed product design for A1-A3 stages; Cradle to Gate (Author)

	Density (kg/m <sup>3</sup> )	Thermal conductivity (W/mK)	Compressive strength (MPa)	GWP-Biogenic (A1-A3) (kg CO <sub>2</sub> e/m <sup>3</sup> )	GWP-Fossil (A1-A3) (kg CO <sub>2</sub> e/m <sup>3</sup> )	Net GWP (A1-A3) (kg CO <sub>2</sub> e/m <sup>3</sup> )	Raw materials	Recyclability	Source
Scenario A				-477	417.15	-59.85	Mycelium, Hemp, Bamboo	Completely biodegradable	Multiple, mentioned in text
Scenario B (improved)	208	0.04-0.07	1.157	-477	330.6	-146.4			
Expanded polystyrene (EPS)	20	0.036	0.17- 0.33	0	60	60	Polymers, natural gas	Decades, century	Livne et al., 2022; EUMEPS EPS EPD
Infill concrete blocks	578	0.8	15	0	157	157	Cement, Sand	Years, decades	EPD: HH Celcon concrete block

The transport phase accounts for the logistical impact of procuring the bamboo reinforcement from its origin in India to the fabrication facility in the Netherlands. Given the material's specific point of origin and the necessity for quicker delivery of the hand-cut bamboo strips, the logistics model assumes international air-freight transport.

The carbon emissions associated with this module were calculated referring to the EN-16258 standard for the quantification and reporting of greenhouse gas emissions for transport services. The total environmental impact was determined by applying a standardised emission factor of 0.8 kg CO<sub>2</sub>e/t-km to the product of the total transit distance and the mass of the bamboo shipment.

#### A3: Manufacturing

High energy processes like inoculation, incubation and thermal deactivation were

assumed to have industry scale numbers for fair comparison to other conventional materials. The Dutch low-voltage electricity mix was approximated as 0.4 kg CO<sub>2</sub>e/kWh based on European electricity emission datasets and LCA databases (ecoinvent v3.x; EF 3.0 characterisation).

### 15.4.3. Results

MBC achieves a net-negative Global Warming Potential (GWP) of -59.85 to -146.4 kg CO<sub>2</sub>e/m<sup>3</sup>(Table 16). In contrast, EPS and concrete have positive net GWPs of 60 and 157 kg CO<sub>2</sub>e/m<sup>3</sup> respectively. This net-negative score relies entirely on biogenic carbon storage to offset high manufacturing emissions. The fossil GWP for MBC ranges from 330.6 to 417.15 kg CO<sub>2</sub>e/m<sup>3</sup>, which exceeds the fossil emissions of both EPS and concrete.

For material mass, MBC has a density of 208 kg/m<sup>3</sup>. It bridges the gap between lightweight

EPS (20 kg/m<sup>3</sup>) and heavy concrete (578 kg/m<sup>3</sup>). Other physical properties position MBC as a direct substitute for EPS rather than concrete. Thermally, MBC acts as an effective insulator. Mechanically, it provides more compressive strength than EPS but lacks the structural capacity of concrete. In conclusion, MBC serves as a viable, carbon-storing replacement for EPS in non-load-bearing insulation. However, its energy-intensive production process and low compressive strength relatively remains a limitation.

The LCA of the lab-scale prototype (Scenario A) reveals that the environmental profile is dominated by two primary factors: the logistical impact of international air-freight and the high energy demand inherent in laboratory-scale fabrication. While the analysis confirms the carbon-storage potential of the biogenic inputs (hemp and bamboo), the initial GWP is disproportionately higher by the energy-intensive processing required for small-batch manufacturing. Specifically, the necessity of maintaining sterile environments via laminar flow, active incubation cooling and heating and the prolonged thermal deactivation cycle (40°C for 24 hours) results in an energy intensity that is unsustainable for industrial-scale application.

#### **Scenario B: Optimisation and Mitigation Strategies**

To improve the environmental performance of the composite system, Scenario B proposes a shift toward localised production and passive optimisation. The following mitigation strategies are proposed to transition the current lab-scale methodology toward a lower-impact industrial framework:

- Localised sourcing: Eliminating international air-freight by establishing localised supply chains for bamboo within the Netherlands is the most significant strategy for reducing the total GWP.
- Passive incubation: Rather than utilising

active, energy-intensive incubation fridges, investing in insulated, climate-controlled dark rooms leverages passive thermal mass and environmental control. This shift significantly reduces the electrical energy requirement per m<sup>3</sup> of MBC produced.

- Refined deactivation protocols: The thermal deactivation cycle can be optimised by transitioning to a dual-stage process. Replacing extended oven use with a prolonged, passive air-drying phase allows for a reduction in time to approximately 18 hours.

- Pasteurisation over sterilisation: Shifting the production protocol from mandatory sterilisation to optimized pasteurisation for hemp and bamboo substrates during the pre-processing stage.

Scenario B demonstrates that the environmental impact of the composite system is not an inherent property of the material, but rather a function of the production process. While Scenario A highlights the storage capacity of biogenic MBCs, Scenario B establishes that industrial scalability is dependent on local sourcing, passive infrastructure and optimised energy-use protocols. By addressing these critical bottlenecks, the environmental performance of the MBC system can be substantially improved, rendering it a viable, low-carbon alternative for the building industry.

#### **15.4.4. End-of-Life (EoL)**

##### **Disposal, Waste Processing, and Deconstruction (C1–C4)**

The environmental impact of the EoL phase for MBCs is inherently lower than that of conventional building materials due to the organic nature of the substrate. As MBCs are composed of biodegradable lignocellulosic fibers, they do not require energy-intensive deconstruction (C1) or hazardous waste processing (C2). Under typical waste management scenarios, the end-of-life stage assumes industrial composting or

anaerobic digestion. In these environments, the mycelial binder and hemp substrate are mineralised into organic matter, effectively returning the sequestered biogenic carbon to the soil (C4). The carbon footprint of transport (C2) during this phase is contingent upon the proximity of the composting facility to the demolition site. However, given the composite's lightweight nature, these logistical impacts are considered to be lower compared to the production stage (Jones et al., 2017).

#### **Reuse, Recovery, and Recycling Potential (D)**

Two distinct pathways can be explored for circularity: material recovery and mechanical reuse. Unlike synthetic rigid cellular plastics, which are often non-recyclable after failure, the bamboo reinforcement scaffold within the composite system can be mechanically separated and recovered (Barta et al., 2024). While the mycelial matrix degrades, the woven bamboo mats maintain structural integrity and provided they have not suffered severe moisture-induced decay, can be repurposed in non-load-bearing applications or shredded for fibre-board reinforcement. Furthermore, the ability to “regrow” the composite where damaged blocks are shredded and used as inoculable substrate for new growth cycles represents a high-potential circular recovery strategy (Bhanja et al., 2022).

# 16.0

## Research conclusion & reflection

### 16.1 Discussion and Conclusion

The discussions and the conclusions will be shared based on scientific perspectives that were obtained during the process while answering all the sub-questions and research question of the thesis.

#### a) Material composition

- **What types of substrates are usually used for the production of MBCs?**

The production of MBCs commonly uses lignocellulosic agricultural and wood-based waste materials as substrates. That is because they provide nutrients and structural support for fungal growth. The reviewed studies show that they generally fall into categories of woody biomass such as wood chips, beech sawdust and wood veneer and fibrous agricultural residues like hemp, straw, cotton stalks and bamboo. These findings also indicate that these are the main substrates sources for MBC production due to their availability, biodegradability and compatibility with mycelial growth. Additionally, nutrient-rich additives like wheat bran, coffee grounds and pineapple fibres are frequently incorporated to supplement the primary substrate and enhance mycelial growth.

- **How does the type of substrate**

**material & its composition affect its binding efficiency with mycelium?**

Studies indicate that fungal hyphae develop interconnected filament networks that mechanically bind substrate particles together. The effectiveness of this bonding depends on fungal species selection, substrate composition, fibre distribution, matrix-to-fibre ratio and processing conditions. Substrates with suitable surface area and nutrient content support stronger mycelial attachment and denser network formation. Overlapping veneer layers yielded a higher bond strength (0.36 MPa) compared to a single veneer strip (0.34 MPa) due to enhanced growth in between the overlapping layers. However, very dense mycelial networks do not always achieve improved binding quality, indicating that bonding performance depends on both substrate and mycelial interaction.

- **What is the optimal material form & its porosity to achieve the adequate density in turn helping with the structural capacity?**

Structural capacity requires the right balance between fibre distribution, matrix-to-fibre ratio and density of the material. Excessive fibre content may lead to stress concentration and weaker structural performance. Substrates reinforced with natural fibres, including pineapple and bamboo fibres demonstrated improved compressive behaviour due to better stress distribution within the matrix. In addition, denser and more uniform composites were observed to exhibit improved structural integrity and crack resistance.

- **What porosity characteristics support effective mycelial growth while maintaining standardised material thickness?**

Effective mycelial growth relies on developing highly porous, interconnected network of hyphae. Controlled porosity allows oxygen diffusion, moisture regulation and hyphal expansion during incubation. Maintaining stable humidity, temperature, ventilation and standardised mould

geometry was identified as necessary for achieving consistent thickness and homogenous mycelial growth. One of the study concluded in the experiment with 50% porosity being the right balance to enhanced mycelial growth.

- **What are the prevailing test results of mechanical (tension & compression) characteristics of MBCs?**

While MBCs show promise, their precursor values are not yet close enough to market benchmarks for standalone load-bearing structural applications without standardised "compression-only" architectural forms. Reported compression strengths vary significantly based on its composition. Values ranging from as low as 93 kPa to a peak of 2920 kPa. Compressive strength generally peaks at lower fibre reinforcement levels of 10%. Flexural strength values ranging from 60 kPa to 450 kPa with 30% fibre content. *Pleurotus ostreatus* was identified as one of the most common fungal species due to its dense mycelial growth, faster colonisation rate and improved mechanical performance.

#### b) Reinforcements

- **What is the current status quo of MBCs for fabrication and reinforcement strategies that have enabled MBCs to perform in load-bearing structural applications?**

Current status quo reflects a transition from non-structural towards more ambitious load-bearing structural implementations. Primarily they are achieved through a combination of geometric optimisation and integration of secondary structural frameworks. Structural designs often utilise modular interlocking elements or compression-only architectural forms (such as arches). Heat-pressed composite showed the highest structural performance due to increased density and improved interfacial bonding. Timber-supported panels and bio-welded monolithic systems are also being explored as methods to improve load transfer and structural continuity. For fabrication, leading strategy involves

embedding a form composed of natural fibres or custom 3D-printed framework directly into the grown substrate. In these hybrid systems, reinforcement structure acts both as the guide to the mycelial growth and primary load-bearing element, with mycelium acting as an insulative, stabilising binder.

- **How can reinforcement scaffold geometry improve compressive strength in MBCs?**

Designed scaffold systems provide better control over porosity, airflow, density and material distribution, which directly affects the growth and structural performance. Geometric optimisation allows the material to carry loads primarily through compression rather than bending. The precise geometry of the scaffold dictates how mechanical stress is distributed through the composite block. In addition, woven and lattice based geometries create interconnected reinforcement paths that enhance mechanical interlocking between fibres and mycelial matrix.

- **What reinforcement forms have proven to be or are a potential to improve compressive strength in MBCs?**

3D-printed porous scaffolds and continuous wood-veneer lattices have been successfully experimented as internal frameworks that significantly improve resistance to compressive forces. 2D woven wicker-lattices and rigid rattan frameworks (as seen in load-bearing furniture prototypes) are highly effective at guiding mycelial growth while taking up the primary structural role to support heavy weights. The direct inclusion of high-strength natural fibres like hemp, jute or straw acts as a micro-reinforcement form. These fibres increase the density and tensile properties of the resulting matrix, resulting in improved overall compressive strength. Similarly, Kagome lattice technique was a potential to further explore similar properties in MBCs.

#### c) Bamboo reinforcement

- **What is the compatibility of bamboo with mycelium that serves as a stiff reinforcement scaffold material to execute the forms?**

Bamboo functions highly effectively as a lignocellulosic substrate material, providing the essential nutrients that mycelium can feed on and bind to during the growth. Compared to loose particulate substrates, bamboo reinforcement provides improved structural stability while allowing mycelium to mechanically bind within the scaffold system. Its high stiffness is also a favourable characteristic for the scaffold. The material is suitable for the reinforcement system because it can be bent, layered and shaped into controlled geometries with the help of weaving without losing structural integrity.

- **Which weaving patterns in bamboo with the right porosity for mycelium to grow help in designing higher compressive strength reinforcement?**

Kagome lattice technique as a specific woven geometry offers highly useful design guidelines for optimising weaving. Few examples being triaxial weaving and grid weaving. The porosity and structural behaviour of the bamboo weave are determined by three primary variables: the unit cell size, the thickness of the strip and the width of the bamboo strip. These variables must be carefully balanced to ensure adequate airflow, substrate distribution and healthy mycelial colonisation while maintaining necessary density. In testing these balances, unit cell sizes ranging between 5mm and 10mm, alongside overall porosity ranges between 50% and 90% were systematically evaluated.

**How can mycelium bio-composites (MBCs) be engineered using woven bamboo fibres as reinforcement to achieve increased compressive mechanical properties for load-bearing applications?**

The research demonstrates that growing mycelium within a woven bamboo

reinforcement system can improve the compressive behaviour, structural stability and material continuity of MBCs. The study focused on developing a composite system where mycelium was grown within two bamboo woven mats while maintaining a confined thickness of 50mm. Through multiple stages of experimentation, the research identified important factors like substrate composition, bamboo geometry, porosity, density and fabrication conditions collectively influencing the final mechanical performance of the composite system.

The early stages established the optimal balance of porosity using hemp shives when packed around the bamboo reinforcement. Furthermore, highlighting the critical role of packing density and the mould type. The structural integrity is highly sensitive to how tightly the substrate is packed, right enough for oxygen airflow and mycelium to grow densely. Additionally, the mould must strike a balance of being tightly sealed to prevent harmful contamination yet sufficiently breathable for oxygen diffusion.

Building onto the optimised protocol, experimental comparisons were made with variations of bamboo strips in its thickness, width and origin. It further reveals that a composite utilising 10mm width (large) strips with 0.5mm thickness woven into a grid weave to be yielding higher compressive strength than in comparison to the composites without any bamboo reinforcement, 1.157 MPa and 0.692 MPa respectively.

Further comparing 5mm width (small) to 10mm width (large) composite system, concluding the grid's cell size becomes crucial with the strip width, becoming the deciding factor for structural binding efficiency. All specimens spanning in the later stages consistently confirmed that narrower 5mm bamboo strips created grid gaps that were too small. This restricted airflow and limited mycelial penetration, leading to poor internal growth, weaker bonding and subsequent delamination under stress. In contrast, the larger gaps created

by the 10mm wide strips provided the ideal spatial porosity, allowing the hemp-mycelium substrate to thoroughly penetrate and strongly bind the two mats together. Similar results with the natural bamboo strip from origin type 02 performing better than processed bamboo strip from origin type 01. This largely validates the content from existing literature about the influence of cell-size grid, porosity and density of the scaffold used as reinforcement to the mycelial growth in turn affecting the structural integrity of the composite.

Although the resulting composites still remain below the strength range of conventional structural materials such as concrete, the developed system demonstrates strong potential for lightweight load-bearing applications using interlocking block using modular construction methods. Furthermore, Life Cycle Assessment (LCA) analysis of the product stage concludes the critical importance of the use of biodegradable materials and their negative contribution to the carbon emissions. The findings also establish a foundation for future research into bamboo woven forms, scalable fabrication methods, long-term durability and reinforcement geometries for structural MBC systems.

## 16.2 Reflections

### 16.2.1. Societal reflection

- ***“To what extent are the results applicable in practice?”***

The practical applicability of this research lies in its physical demonstration of a new type of an MBC. It moves the concept of a mycelium-bound woven bamboo mat from theoretical speculation to a validated material system. By documenting how this novel form performs, the research makes a tangible contribution to the growing catalogue of bio-based materials. This allows on the investigation to grow on how an alternative bamboo configuration can enhance structural behaviour while remaining aligned with circular and low-impact construction practices. While current results are preliminary, they provide the essential starting point required to guide the rigorous future prototyping and testing needed to achieve commercial viability and practical market integration. The project not only contributes to a material proposal but also a framework for further exploration into reinforced MBC systems.

- ***“To what extent has the projected innovation been achieved?”***

The primary objective of innovating a structural application of woven bamboo within a mycelium matrix has been partially achieved. This basically happened by redefining the reinforcement as a woven scaffold rather than a mere additive substrate. While the current iterations have not yet achieved highest structural thresholds, the project successfully delivers a foundational proof of concept. It serves as a necessary segue to subsequent research to optimise the strength of the composite system.

- ***“Does the project contribute to sustainable development?”***

The project contributes significantly towards sustainable development by

embedding circular principles throughout the material's lifecycle. The system utilises agricultural residue as its primary substrate, transforming biological waste streams into functional building materials. The raw materials used, all of them store carbon positioning the fabrication process as potentially carbon-negative. The proposed modular construction system further supports sustainable construction practices through reduced material waste and the potential for disassembly and reuse. At the end of its lifecycle, the composite remains fully biodegradable, allowing the material to re-enter natural cycles without generating long-term waste. Although the system requires further optimisation before large-scale market implementation, it is a potential as a regenerative alternative to conventional carbon-intensive construction materials.

**- "What is the impact of your project on sustainability (people, planet, profit/prosperity)?"**

The bio-composite directly enhances human health and indoor environmental quality. Its porous, mycelial network acts as a passive air filtration system. Its inherently organic composition eliminates the toxic surface chemicals in conventional construction materials. The material also introduces a biophilic aesthetic establishing visual connection between the built environment and natural ecological systems. The material system presents a positive environmental profile with a fully biodegradable and carbon-negative cycle that does not deplete ecological resources. This research catalyses a necessary cultural shift while redefining material needs. By proving the viability of grown assemblies, the project introduces new socio-cultural values to the industry, demonstrating that regenerative design can and must become foundational.

**- "What is the socio-cultural and ethical impact?"**

This project operates at the intersection of vernacular craft and advanced bio-

fabrication, fundamentally challenging extractive building practices. The integration of woven bamboo mats with mycelial growth represents a shift, transitioning from inert, manufactured components to active, cultivated systems. This introduces a dialogue concerning the ethical responsibility of the architectural discipline to foster construction methodologies that are both biologically regenerative and universally accessible.

**- "How does the project affects architecture / the built environment?"**

The use of mycelium in construction has been related to non-structural applications such as thermal insulation or acoustic paneling. This project adds to the discussions of engineering a structurally active, woven bamboo scaffold to be a step closer to fulfilling load-bearing requirements. It also advocates for architecture that is designed for disassembly, ensuring that structures function as temporary material banks rather than permanent ecological liabilities.

## 16.2.2. Academic reflection

My growing interest in the world of bio-based materials led me to further explore the potential of mycelium composites, given that I had worked with mycelium briefly in one of the electives in the first year of the masters. I was always fascinated by the structural possibilities of grown materials in the built environment. Moving from a beginner's perspective to testing and analysing structural forms has been a steep yet rewarding learning curve. The following section offers a reflection on this journey with the MycoMax project.

**- "How is your graduation topic positioned in the studio?"**

My graduation topic, centered on the potential of MBCs as a building material, closely aligned with the studio's emphasis on bio-based material research, circularity and structural innovation. A significant part of the thesis is dedicated to material research and material innovation. By systematically experimenting with various fabrication methods and drawing upon existing literature, the project aims to develop an innovative, structurally viable material system. A broad part of the studio's interest lies in bio-based materials' market readiness through enhanced structural abilities and efficient product design. This performance-based approach addresses the studio's emphasis on research that combines design with engineering precision.

**- "How did the research approach work out (and why or why not)? And did it lead to the results you aimed for?"**

The research approach was fundamentally driven by the primary objective: enhancing the load-bearing capabilities of MBCs. Initially, the research faced significant complexity due to the high degree of variability in biological material composition. Industrial production methods for MBCs currently lack universal standardisation, establishing a rigorous, reproducible fabrication protocol became a critical, secondary research

objective in itself.

To progress within this, the methodology relied on diverse existing studies to identify the substrate formulations most compatible with bamboo reinforcement. Simultaneously, the research expanded to explore specific bamboo scaffold geometries optimised for compressive resistance. Ultimately, this structured approach was successful. It provided a clear framework to deeply study about the MBC fabrication process, isolating the primary and secondary substrates. That translated into theoretical, compression-centric designs into a tangible and functional prototype.

### SWOT analysis:

#### Strengths:

The primary strength of this research lies in its successful synthesis of multiple interdisciplinary studies, spanning microbiology, materials science, and structural engineering, into a cohesive, novel hypothesis. Translating theoretical data into a tangible, load-bearing prototype demonstrates the validity of the approach. Furthermore, continuous consultation and input from bio-materials experts significantly enriched the academic rigor, precision and practical relevance of the fabrication protocol.

#### Weaknesses

The research faced many constraints due to the highly variability of biological production. A specific method-based weakness was my entry-level proficiency in manual bamboo weaving, which made it difficult and increased the complexity and speed of fabricating the initial scaffold geometries. Additionally, logistical challenges regarding the procurement of bamboo and many other raw materials introduced significant time constraints and limited the volume of physical testing.

#### Opportunities

The proof-of-concept establishes a strong foundation for ongoing research. There are

substantial opportunities to systematically develop this material system further. Future trajectories can focus on optimising the internal micro-geometry of the scaffolds, exploring complex three-dimensional architectural forms and scaling the interlocking block design for broader industrial application.

### Threats

The primary risk to the validity of the experimental results comes from the fabrication environment. Conducting portions of the experiments and incubation outside of strictly controlled, sterile laboratory settings posed a threat. This non-laboratory approach increased the material's susceptibility to contamination and environmental fluctuations, ultimately confirming that rigorous environmental controls are strictly necessary for the scalable production of MBCs.

#### *- "How are research and design related?"*

In this thesis, material research fundamentally drove the design process. The experimental development of the composite system dominated the project timeline and scope. The physical and structural capabilities of the material directly dictated the architectural design choices.

The final interlocking block design remained at a preliminary, proof-of-concept stage. Innovating and standardising the novel biological material required the vast majority of the research effort. The product design could only advance speculatively and simultaneously once the material's mechanics were proven and understood. The material research acted as the necessary foundation and the design served as the preliminary structural application of those findings.

#### *- "Did you encounter moral/ethical issues or dilemmas during the process? How did you deal with these?"*

The first dilemma involved the sample batches in Stages 01 and 02A. Contamination ruined these samples. There is a common pressure in research to present only successful results. Omitting these failures would make the process look easy. However, this is not honest. This was resolved through strict data transparency. The report clearly states that material characterisation did not happen for these batches due to contamination. Acknowledging this failure provided a valuable lesson. It proved that sterile environments are strictly required for biological fabrication.

The second dilemma involved the environmental claims of the project. The main goal is to create a low-carbon building material. However, the bamboo reinforcement was air-freighted from India. This mode of transport caused high carbon emissions. It is unethical to ignore these emissions and call the material fully green. This was resolved using objective Life Cycle Assessment (LCA) methods. The transport emissions were clearly calculated in Scenario A. To fix this conflict, Scenario B was proposed. It outlines a shift to local sourcing in the Netherlands to achieve actual sustainability.

The third dilemma occurred when production moved from the STV lab to a home setup. Working with fungal spores outside a lab presents health and safety risks. The ethical issue was whether to proceed in an uncertified space just to meet project deadlines. This was resolved by creating strict, improvised sterile protocols. Great care was taken to replicate lab conditions at home. This protected personal safety and ensured the final test blocks were valid.

Artificial Intelligence (AI) tools were used during the writing and documentation stages of this research as a supplementary support tool. Their role was limited to linguistic refinement tasks such as grammar correction, sentence restructuring and improving the clarity of preliminary written content.

## 16.4 Recommendations

Several limitations identified during this research present opportunities for future development and investigation:

- Bamboo woven reinforcement should explore complex, fully three-dimensional scaffold forms. Developing 3D woven reinforcement topologies will likely enhance the composite's ability to distribute multi-directional compressive and tensile loads, expanding its applicability load-bearing applications.

- Current methodologies involve inoculation at the start of the process. Future research should explore phased or segregated inoculation techniques. For example, pre-colonising the bamboo scaffold and the hemp substrate separately before combining them into the final mould could be highly beneficial. This approach may yield a denser, more uniform interfacial bond and provide greater control over the quality of the final growth phase.

- A rigorous, standardised protocol for substrate formulation is required. Future studies should conduct extensive testing to define the exact optimal ratio of mycelium spawn to secondary substrate (hemp), alongside specific nutritional additives. A highly controlled recipe is necessary to reduce the biological variability of the material and ensure reproducible mechanical results.

- The design of the fabrication molds requires significant refinement. Future iterations must engineer mould materials and geometries that achieve a precise balance. The molds must provide sufficient oxygen diffusion, while simultaneously maintaining a strictly sealed boundary to eliminate the risk of contamination.

- Laboratory-scale fabrication is highly energy-intensive and tailored to a small batch. Future research focused on industrial scale-up must actively eliminate high-energy processes. Developing passive

incubation infrastructure, extended air-drying deactivation cycles and low-energy pasteurisation methods is necessary to maintain the material's productability and environmental viability.

22/05/2026

10 days later...

31/05/2026



*Stage 04: For Demonstration, still growing...*



*Stage 04: Interlocking blocks*

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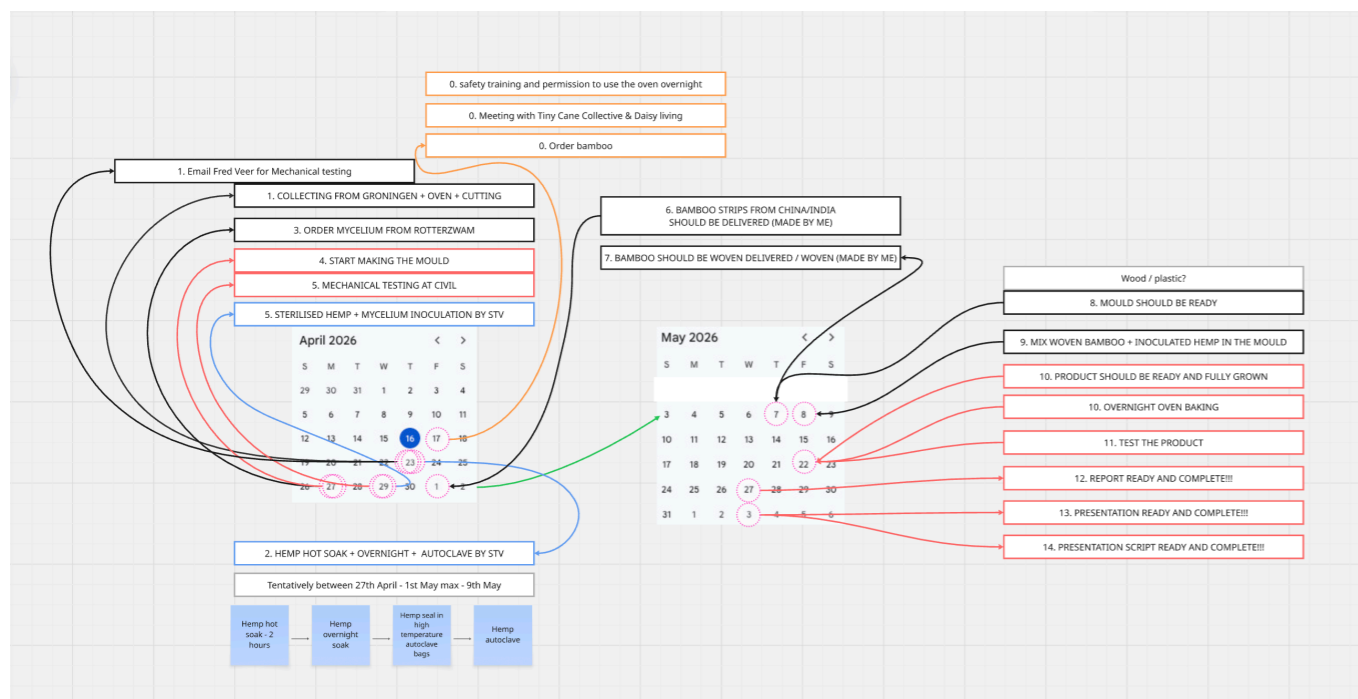
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# 18.0

## Appendix

Constants	Thickness of the strip	Width of the strip	Number of matts	Matt joined or not	Source
<i>(decisions that require literature / logical reasoning)</i>	0.5mm, 1mm	5mm (S), 8mm (M), 10mm (L)	two, three, four	yes or no	IND, CHN
Oyster mushroom spawn					
Primary substrate : Bamboo	0.5 mm	S		No	CHN
Secondary substrate : Hemp hurds / shives	0.5 mm	L		No	CHN
3 hours boiling	0.5 mm	S		Yes	CHN
30 mins sterilisation	0.5 mm	L		Yes	CHN
121°C temperature	1 mm	S		Yes	CHN
2 matts joined	1 mm	L		Yes	CHN
	1 mm	S		Yes	IND
	1 mm	L		Yes	IND
	0.5 mm	L		Yes	IND

Appendix 01: Variables filtering (Author)



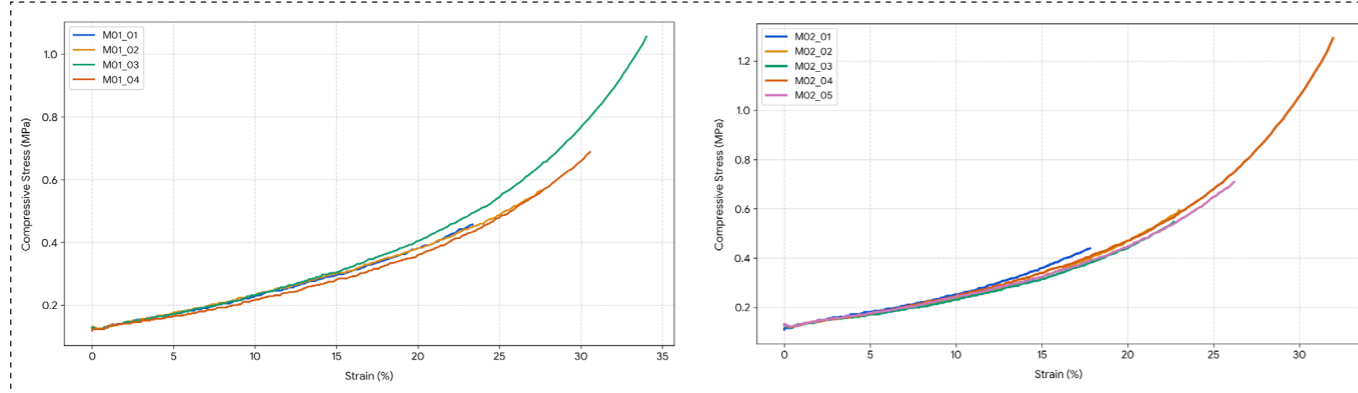
Appendix 02: Scheduling for all the 2 week long processes (Author)

### You will need:

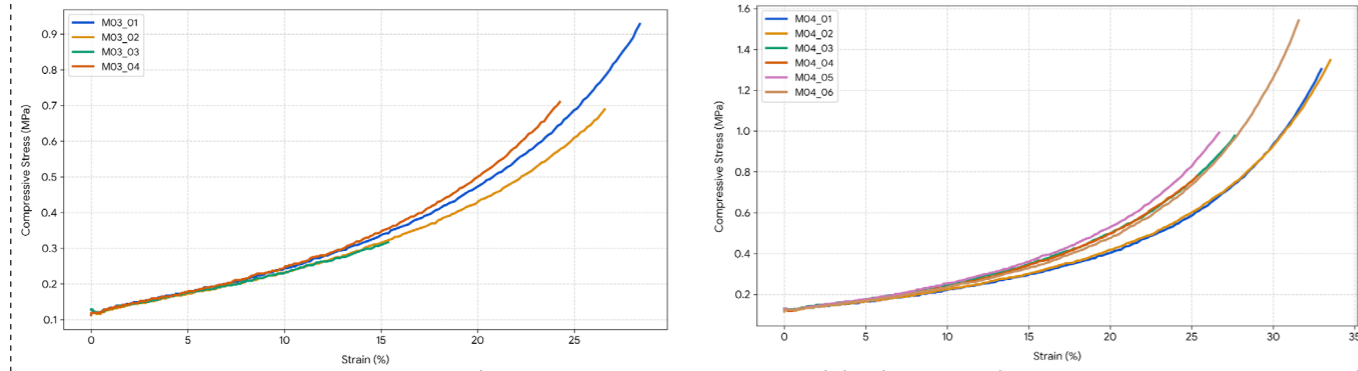
- o Ethanol (alcohol to disinfect)
- o Plastic wrap
- o Scissors
- o Gloves
- o Flour (30g per 1 kg substrate)
- o Sculpting mix (optional)
- o Growth Form, if not ordered
- o Large bowl
- o Kitchen scale



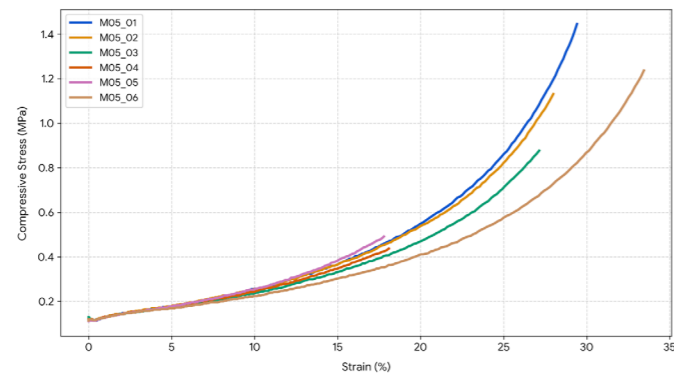
Appendix 02: DIY recipe (Source: GROWN bio)



**Appendix 3a:** Stress-strain curve for M01 (only hemp) (left) and M02 (Small width 5mm, origin type 02) (right) (Author)

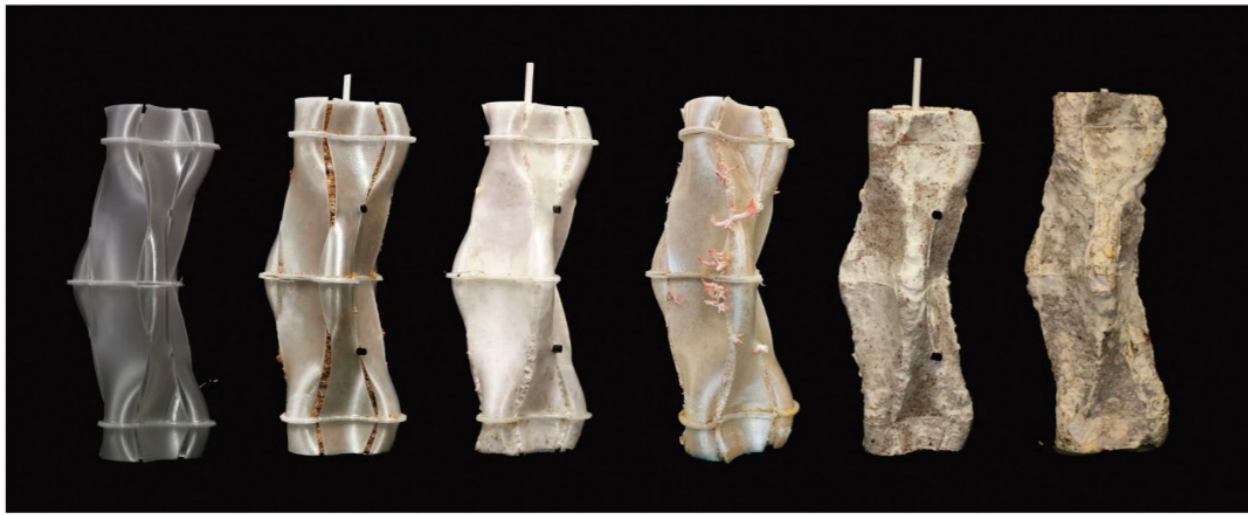


**Appendix 3b:** Stress-strain curve for M03 (Small width 5mm, origin type 01) (left) and M04 (Large width 10mm, origin type 02) (right) (Author)

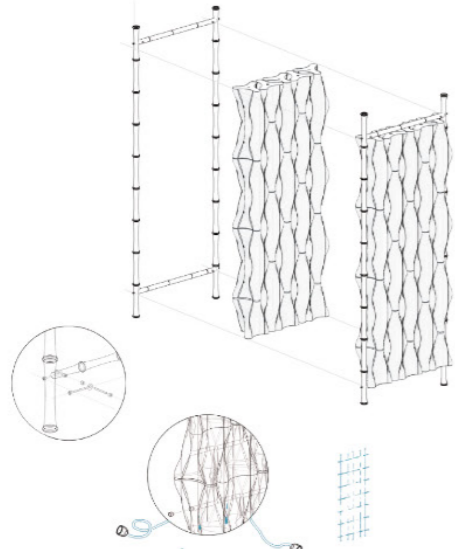


**Appendix 3c:** Stress-strain curve for M05 (Large width 10mm, origin type 01) (Author)

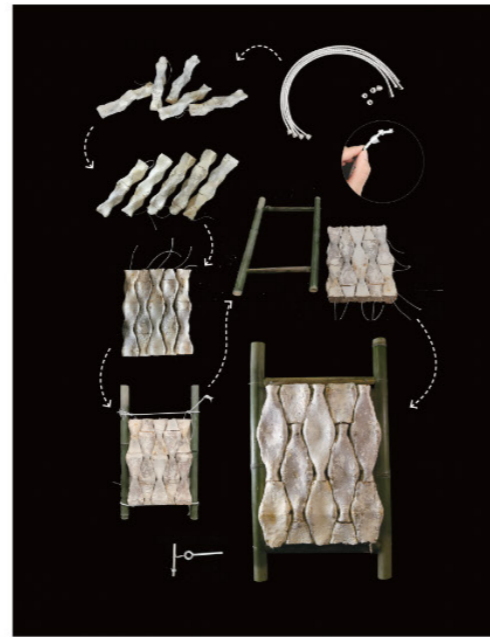
**Appendix 03:** Stress-strain curves for each specimen group in Stage 2B (Author)



**Endless Fungi – Mycelium Composites: Bridging Architecture and Agriculture with Bio-Modules for Sustainable Design AUGUST 2025**



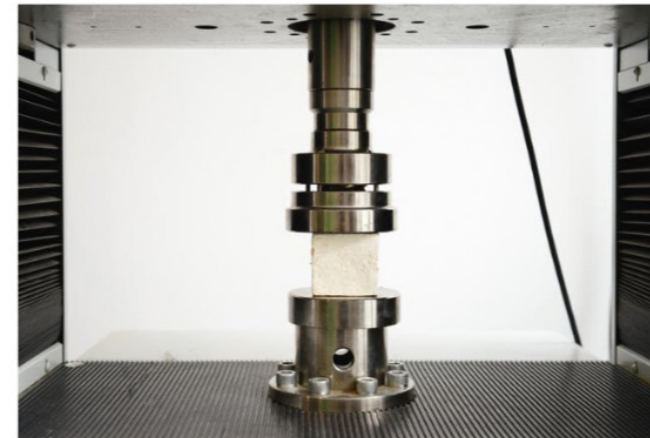
[https://www.dg.architektur.tu-darmstadt.de/studium/student\\_work/master\\_thesis/endless\\_fungi/endless\\_fungi\\_en.jsp](https://www.dg.architektur.tu-darmstadt.de/studium/student_work/master_thesis/endless_fungi/endless_fungi_en.jsp)



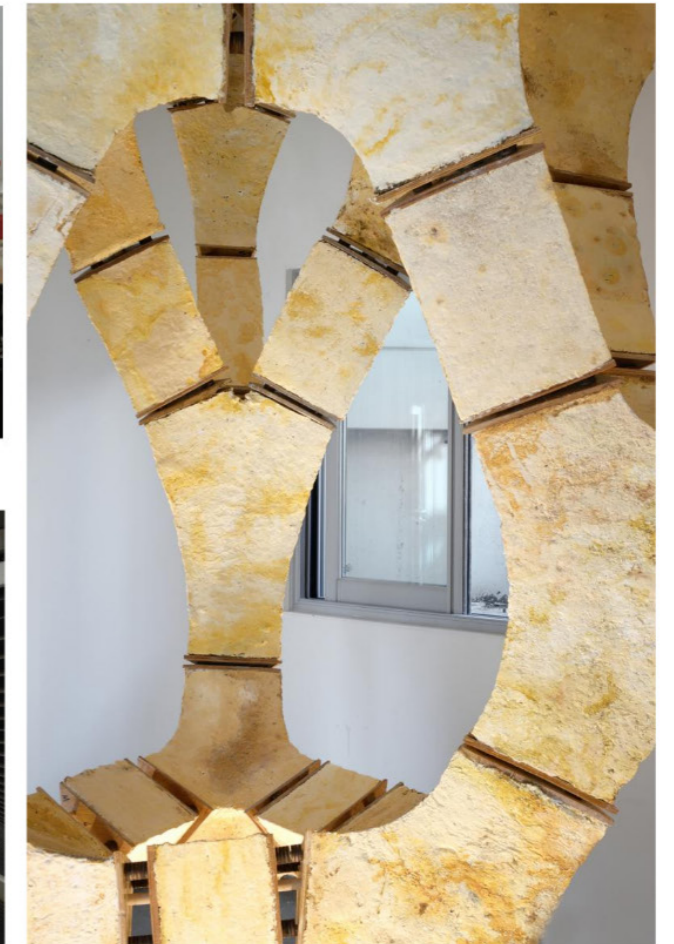
**Appendix 04: Endless Fungi – Mycelium Composites: Bridging Architecture and Agriculture with Bio-Modules for Sustainable Design AUGUST 2025**



It is important to work sterile and keep competing bacteria or mushroom spores away from the material. To activate the mushroom, the nutrient needs to be sufficiently watered. (Photo © Carina Teteris)



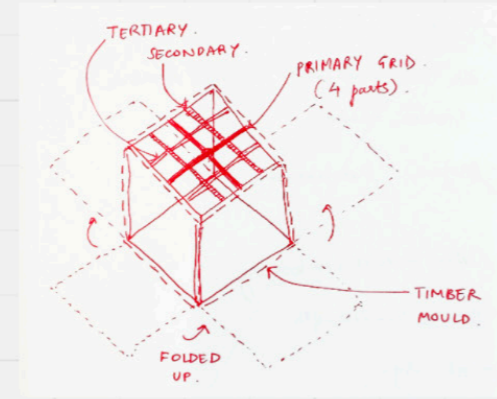
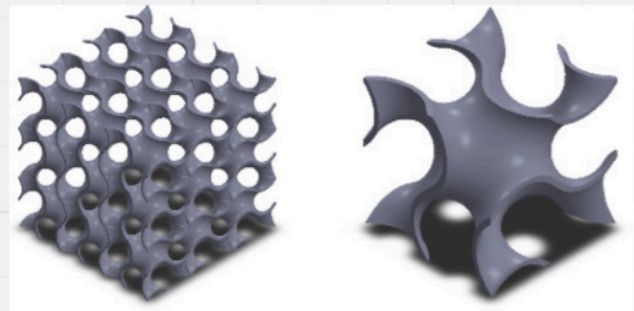
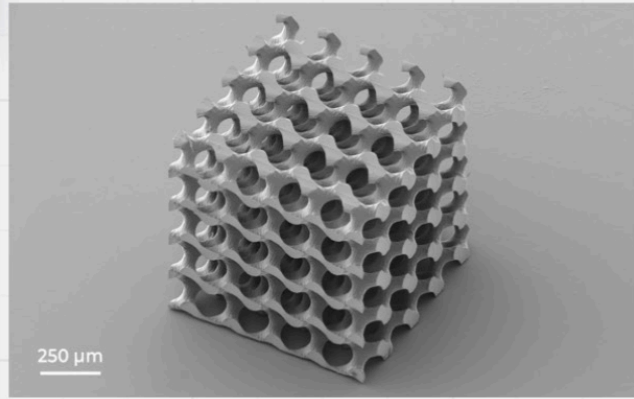
Mushroom mycelium is a weak material with a very low bending and tensile capacity. However, tests showed that the compressive strength of the material is sufficient for certain structural applications. (Photo © Carina Teteris)



Assembly (Photo © Sustainable Construction, KIT and BRG, ETH Zürich)

**Appendix 04: MYCOTREE by KIT Karlsruhe + ETH Zürich + Singapore-ETH Centre | 5. September 2017**

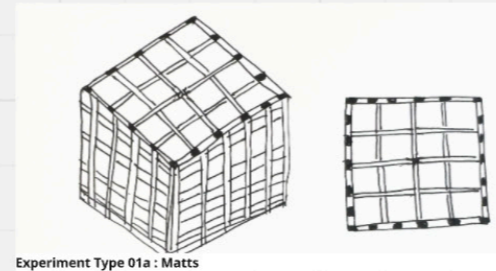
STAGE 02 - EXPLORATORY WAYS OF CONSTRUCTING



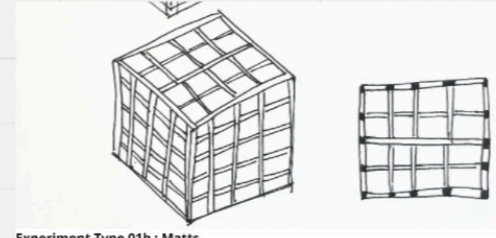
Gyroids get their strength from:

- no straight struts
- continuous curvature
- evenly distributed load paths

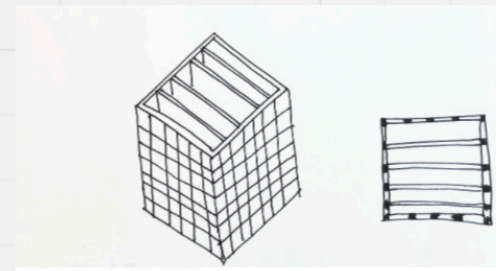
TPMS geometry refers to Triply Periodic Minimal Surfaces, which are repeating, smooth, and porous structures used in engineering for applications like heat transfer and lightweight materials.



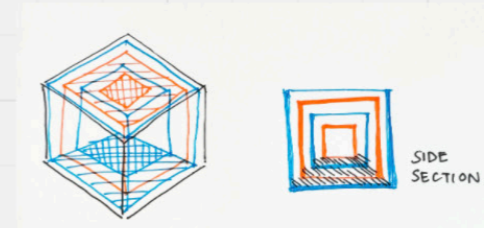
Experiment Type 01a : Matts



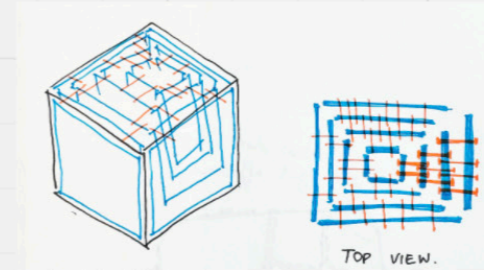
Experiment Type 01b : Matts



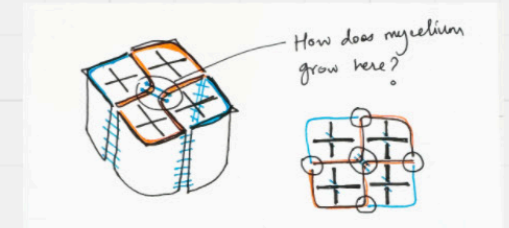
Experiment Type 01c : Matts



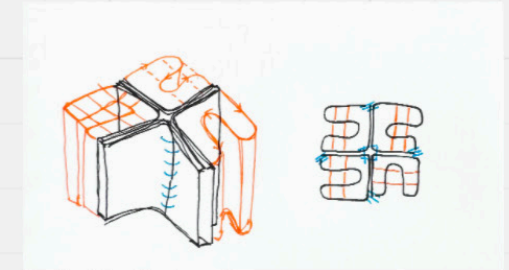
Experiment Type 02a : Box inside a box



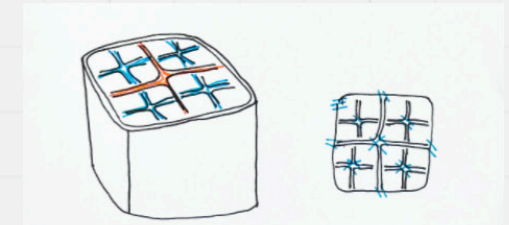
Experiment Type 02b : 4 corners



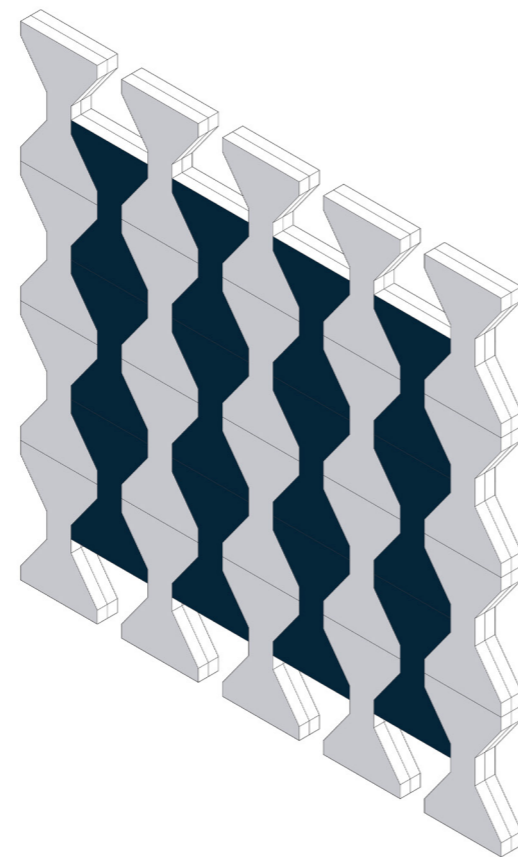
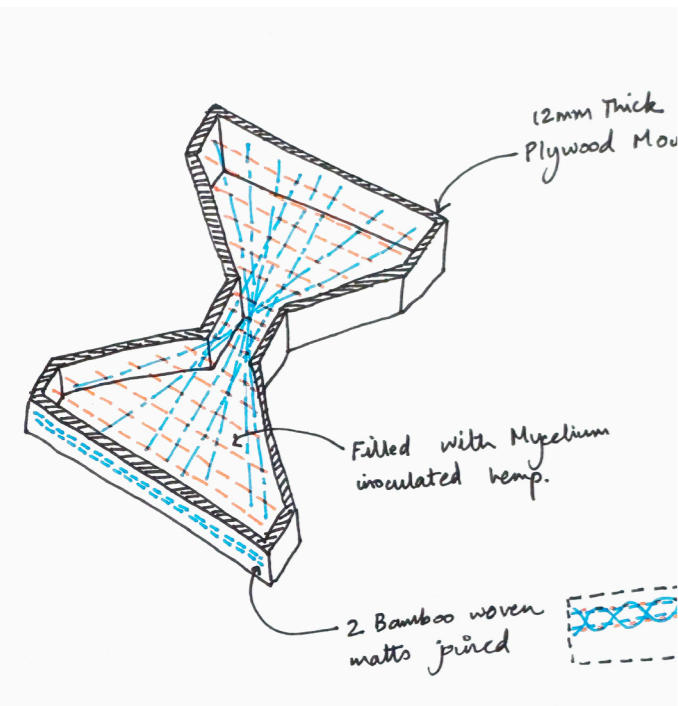
Experiment Type 03a : 4 curved in corners



Experiment Type 03b : 4 curved in corners



Experiment Type 03c : grid inside a grid








Goal and Scope: Compare the embodied energy and carbon of a lab-scale mycelium brick to a standard fired clay brick in the Netherlands								
Calculate Embodied Energy (EE) and Embodied Carbon (EC) per 1 m <sup>3</sup> of material								
Material	Process	Per brick			Total	kg co2 eq per m3	Reference/Citation	
		qty	Weight/Energy	kgCO <sub>2</sub> e/unit				
HEAT INAC TIVA TION	Oven	40°C for 24 hours	12 kWh	4.8 kg CO2	0.24 kg CO2 eq	1664		
		Pots, spoons						
		Weighing scale						
EQUIP		Gloves		negligible				

Appendix 05c: LCA complete calculations (Author)

	Fungal species	Substrate type	Supplement Substrate	Moisture content	Temperature	Incubation time (days)	Mold type	Drying method
Gyroid case study (Sharma et al.)	G. lucidum (Malaysian feedmills farm ltd.)	1.7mm diameter commercially available composite wood-PLA filament	Peptone, malt extract, agar powder (Sigma aldrich)  The optimal composition of <b>0.1w/v% peptone, 10 w/v% malt, and 2.4w/v% agar</b>  was obtained from the trial experiments.  PMA solution at <b>temperatures between 40–50 °C</b> <b>was perfect</b> , i.e., not too viscous to pass through the pores of the samples and not too thin to stick on the samples.	80% RH	23 degrees	21 days	no mold	48 degrees C in an oven overnight
Enhancing Flexural performance + additives (Amundhan et al.)		<b>Straw (long fibers)</b> was selected for: Higher flexural strength compared to many natural fibers Local availability  Incorporated at: 15% (S1); 30% (S2); 60% (S3) of primary substrate weight  <b>Hemp (short fibers)</b> was selected for: High tensile stiffness Proven mechanical and acoustic performance Sustainability benefits through agricultural waste utilization  Incorporated at: 15% (H1); 30% (H2); 60% (H3) of primary substrate weight  Combined formulation (SH): 15% straw + 15% hemp  Tested to evaluate synergistic effects on material properties	- Optimal growth period: 6 days - Wheat flour boosts strength and growth rate - Guar gum improves skin quality and shrinkage control - Straw enhances flexibility and dimensional stability at low percentages - Best-performing and most workable formulation: AS1.2  AS1.2 selected as the standard substrate for subsequent phases, balancing mechanical performance, stability, and manufacturability.	90% humidity	25-26 degrees	not mentioned	sanitized plastic containers	45 degrees and 20% humidity for a period of 4 days using room heaters and a dehumidifier
Mycomerge (Nguyen et al.)	Pleurotus ostreatus	2mm dia rattan (outer layer) + 5mm dia rattan (inner layer)	Short chopped fibres like wood chips + long continuous fibres like hemp  sterilized through pasteurization  cooled down to a temperature at 28 degrees  psyllium husk was added --> to improve material distribution		20-25 degrees (ambient temperature, not controlled)	3 weeks		

Appendix 06: Comparative recipes (Author)



*Until next time,  
in the Chronicles of Mycelium trying to be stronger!*

*We do not give up yet,  
Because good things take time.*