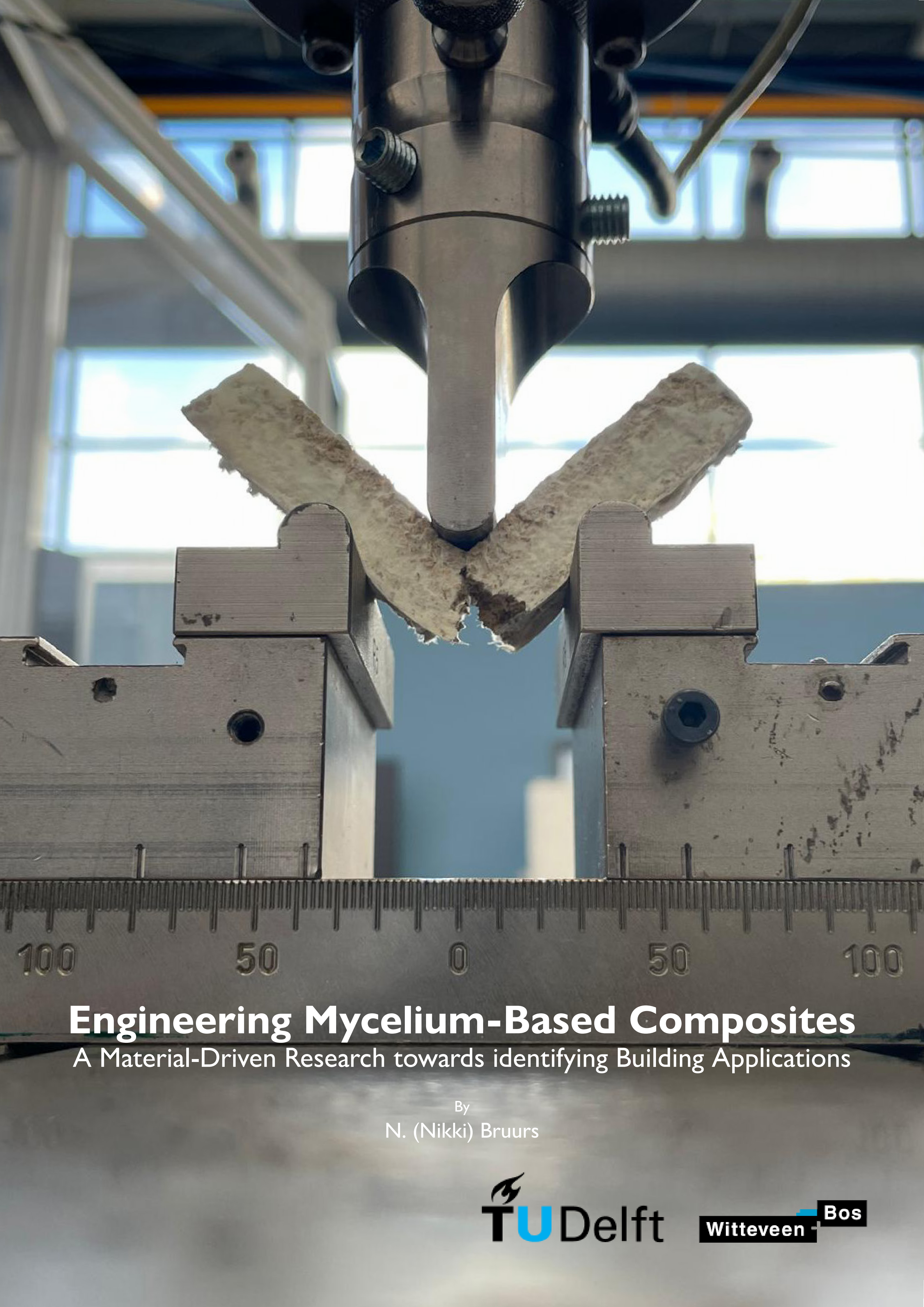

Engineering Mycelium-Based Composites

A Material-Driven Research towards identifying Building Applications

By

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TU Delft

Witteveen Bos

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in partial fulfilment of the requirements for the degree of

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… to be defended publicly on 13.01.2025

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This thesis is confidential and cannot be made public until January 13, 2025.

An electronic version of this thesis is available at http://repository.tudelft.nl/.

"The best way to predict the future, is to create it."

- Abraham Lincoln

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Abstract

This research explores the potential of mycelium-based composites (MBCs) as a sustainable and innovative building material, emphasizing the critical importance of adopting material-driven approaches to fully explore the unique properties of MBC.By focusing on the material itself, this study investigates the processes involved in its manufacturing, the interaction between fungal species and substrates, and the optimal environmental conditions for optimizing its mechanical and functional properties.

Through a multidisciplinary approach combining material science, engineering, and architectural design, this research presents an integrated process of experimentation and prototype development that results in the creation of complex-shaped partition wall blocks. These blocks are made entirely from MBCs, using mycelium as both the primary material and the bio-based binder, highlighting the potential of MBC to replace traditional materials in non-load bearing building applications. The study demonstrates that mycelium-based composites can be engineered into lightweight and biodegradable building components, offering significant advantages in terms of sustainability and circularity.

While challenges remain in terms of the mechanical strength and durability of MBCs compared to conventional building materials, this research highlights the potential for material-driven innovation. The results show several versatile applications such as wall panels, non-structural components, and partition elements. By increasing the knowledge of the properties and behaviour of mycelium-based composites, this study lays the foundation for the integration of bio-based materials into sustainable building practices and encourages further research into optimizing their life cycle and scalability. The resulting innovative partition wall block represents one of the many options possible with MBC, and is a significant step towards a circular, nature-inspired approach to building technology.

Acknowledgements

I would like to express my sincerest gratitude to all those who have provided me with invaluable assistance, encouragement and guidance throughout the course of my thesis.

From the outset, my interest in mycelium had already been initiated within my previous Master's programme, Architecture, where I undertook the course Extreme Architecture in the first and second quarters of the 2022/23 academic year. During this period, we were required to select a research topic of our own choosing, in collaboration with one fellow student. Our chosen topic was the subject of mycelium-based building materials. I would like to express my gratitude to Lex van Deudekom, the studio's BT tutor, and to Nicolette, my former fellow architecture student, with whom I conducted the four-week mycelium research, which proved very useful and valueble during the initial phase of my graduation.

I would also like to express my deepest appreciation to my mentors, Olga Ioannou and Mauro Overend, for their invaluable guidance and for sharing their advanced knowledge and expertise, which has been essential to the successful completion of this research project. During the numerous meetings I have had with each of them, I have learned a lot and they have helped me so well with the whole process. In addition, the quality of this research has also been enhanced by the supervision provided by Nader Merhi from Witteveen+Bos and the rest of the Building Physics and Circularity team, for which I am very thankful as it has made the entire process even more enjoyable. I could ask them any question I have had and this has been extremely beneficial for me.

Furthermore, the research and the experiments would not have been possible without the assistance of Martin Tenpierik, who kindly provided the hotbox and guided me through the installation process for the right conditions. I would also like to express my deep gratitude to Fred Veer. His guidance and knowledge during the mechanical testing phase were invaluable, and I am extremely thankful to him for providing me with invaluable insights and information. Furthermore, I would like to acknowledge the expertise of all the experts who generously shared their knowledge, which proved to be highly beneficial.

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Lexicon

Fungi
Fungi is the plural of fungus. Fungus is a type of living thing that includes around 144,000 different species. This group has many types like yeasts, rusts, smuts, mildews, molds, and mushrooms.
(The Editors of Encyclopaedia Britannica, 2024a)

Mushroom
The fruiting body (umbrella-shaped) of certain fungi.
(The Editors of Encyclopaedia Britannica, 2024b)

Mycelium
The root-like part of fungi, made up of long, branching threads called hyphae.
(Wösten et al., 2018)

Substrate
The material or surface on which an organism lives, grows, or feeds.
(Lelivelt, 2015)

Mycelium-Based Composites
When mycelium is mixed with a substrate, the substrate acts as the filler, and the mycelium hyphae act as the binder to keep the loose material together. After the growing process when the mixture is dried or heated, this becomes mycelium-based composite. (Ghazvinian & Gürsoy, 2022).

Grain spawn
Grain spawn is a process whereby mushroom mycelium is grown on a sterilised grain substrate. It is used to multiply mycelium and inoculate bulk mushroom substrates. The grains provide nutrients for the mycelium to feed on and grow. Once fully colonised, the grain spawn can be easily broken into small pieces. These small pieces of mycelium-coated grain can be distributed evenly throughout a bulk substrate, creating multiple inoculation points and speeding up colonization. (Sayner, 2024)

Hedelcomposite
Hedelcomposite is composed of sterilised sawdust residuals and inoculated with mycelium. It is ready for immediate use. The objective is to cultivate biodegradable mycelium objects with Hedelcomposite in a period of approximately one week.
(HedelComposite - 10KG ~20L | Kineco Mycelium, n.d.)

Circular Economy
A system where materials will never become waste and nature is regenerated.
(Circular Economy Introduction, n.d.)

Incubation
The period during which mycelium grows and spreads through a substrate, forming a dense network of hyphae. In laboratory conditions, uniform conditions of temperature and humidity must be maintained to ensure the development of certain experimental organisms, especially bacteria. (The Editors of Encyclopaedia Britannica, 1998)

Inoculation
The process of introducing a microorganism into a new environment - or substrate. (The Editors of Encyclopaedia Britannica, 2024c)

Acronyms

ASTM	American Society for Testing Materials
BT	Building Technology (MSc track)
EOL	End Of Life
Gan. luc.	*Ganoderma lucidum*
LCA	Life Cycle Assessment
MBC	Mycelium-Based Composite
MPa	Mega Pascal (unit of pressure)
N	Newton (unit force)
Pl. ostr.	*Pleurotus ostreatus*

01 Introduction

01 Introduction

1.1 Problem statement

In 2019, the Dutch government introduced the Climate Agreement as part of the country's climate policy. It is therefore necessary to achieve a reduction of 95% in greenhouse gas emissions by 2050. (Rijksoverheid, 2019). The building sector account for 38% of all energy-related CO2 emissions (IEA, 2020). In the context of striving towards a future that is almost carbon-free, it is essential to attempt to reduce these emissions by transition to a circular economy. A circular economy is based on three principles, according to the Ellen MacArthur Foundation (Circular Economy Introduction, n.d.):

- Eliminate waste and pollution;
- Circulate products and materials (at the highest level);
- Regenerate nature.

In the current economic climate, materials are first extracted from the earth, processed into products and ultimately discarded as waste. This linear process is in contrast to the principles of a circular economy, which is characterised by the reduction of waste and the promotion of reuse and recycling at the highest possible level for all products and materials (Ibid.).

1.1.1 Bio-based materials

One effective approach of reducing the production of waste and CO2 is to identify alternative materials for traditional building construction. Bio-based materials are a suitable option, as they not only reduce the greenhouse gas emissions associated with construction, but they also have the potential to temporarily store carbon and are biodegradable (Galimshina et al., 2022).

Currently, there is a wide variety of bio-based materials available on the market. However, the majority of these materials are chemically treated in order to optimize their performance. As a result of this treatment, the bio-based materials are no longer suitable for reuse or recycling (Dessi-Olive, 2022a).

To fulfil the requirements of a circular economy, waste products could be combined with bio-based materials. The construction industry already uses various bio-based materials, like hemp, straw and bamboo. Recently, living bio-based materials such as algae, seaweed and mycelium have also been introduced to this market. However, many potential uses for these living bio-based materials remain unexplored (Meyer et al., 2020). The present thesis focuses on identifying the mechanical properties of mycelium. By extension, and based on this information, it explores the potential applications.

1.1.2 Mycelium

Mycelium is the vegetative part of fungi characterised by a long, branched and thread-like structure, the hyphae. This hyphae functions as a bio-based adhesive and is used to create a network of extremely dense filaments attached to the organic substrate (Alemu et al., 2022). Mycelium is easily biodegradable or compostable at the end of life of the building component and it is also produced with a minimal carbon footprint (Almpani-Lekka et al., 2022). Additionally, minimal waste is produced during its manufacture process, making it an efficient material to produce in terms of both energy use and waste management (Dessi-Olive, 2022a).

Products based on mycelium are also carbon negative, meaning that they absorb more CO2 than they emit. The process works as follows (Mycelium Composites - Biobased Materials, 2023):

1. CO2 storage in agricultural by-products: Agricultural by-products which have absorbed CO2 during their growth are collected;
2. Processing and growth: These by-products are then chopped and mixed with mycelium. The mixture is cultivated in moulds in order to form the desired products.
3. Distribution: The finished mycelium products are transported.

Although each step in the process generates some CO2 emissions, the overall carbon footprint is negative. This is because the mycelium composites store more CO2 than is released during the entire production and distribution process, when produced on higher scale. (Ibid.)

In this thesis, the characteristics, advantages, limitations and production process will be discussed in the first part: the literature review. Reference projects will be analysed for comparison and interviews will be held with experts. The second part of this thesis, the experimental phase, will be used to test and improve the mechanical properties. In the final part, the integration phase, the results of the mechanical property testing will be used to identify the optimal application and design for this material.

1.2 Research objective

1.2.1 Objective

The main objective of this research is to investigate mycelium-based composites. This research project focuses on the material mycelium-based composite itself, including an investigation of the processes involved in its manufacture, the growth process, the limitations of this process, the optimal combinations of substrate and fungal species, and the mechanical properties of the material. Furthermore, the applicability of this MBC in building elements is considered by comparing the observed mechanical properties and running experiments to test and improve them. The goal is to gain a deeper understanding of the material itself and its mechanical properties, with the aim of enhancing them in order to facilitate their application in the field of innovative building elements. The enhanced material will be subjected to a series of tests, including compression strength and 3-point bending tests. The objective of these experiments is to facilitate a comparison between various combinations of fungi and substrate, as well as between these combinations and other building materials.

1.2.2 Focus

The possibility of mycelium-based composites as an innovative technology is considerable, yet further scientific understanding is necessary to facilitate their incorporation into our everyday lives. The material properties and potential applications of mycelium-based composites are influenced by a number of factors, including:

- The type of fungus used;
- The substrate material;
- The environmental conditions during the growth;
- The shape and design of the used mould;
- The drying and post-treatment technique.

It is evident that there are strong connections between the numerous parameters, and it is a challenging task to analyse, evaluate and compare the outcomes of different experiments. This is due to the fact that the influence of many variables is not yet fully understood. It is therefore evident that a deeper understanding of the scientific principles involved is required in order to facilitate the development of new biological materials and to integrate them into our daily lives. (Vanden Elsacker & Vrije Universiteit Brussel, 2021)

1.3 Research questions

1.3.1 Main question

The main research question to be answered through this thesis is:

> *"How can mycelium-based composites be engineered and optimized for use as a building element in internal applications?"*

1.3.2 Sub-questions

The following sub-questions will be addressed in order to provide an answer to the main question:

1. What is a mycelium-based composite?

1.1 How are mycelium-based composites produced?
1.2 In what building applications may mycelium-based composites be employed?
1.3 What are the advantages and disadvantages of using mycelium-based composites in building elements?

2. What different combinations of substrate and fungal species can be used to make mycelium-based composite suitable for building elements?

2.1 What are the most suitable substrates for optimizing the growth and performance of mycelium-based composites?
2.2 What are the most suitable fungal species for optimizing the growth and performance of mycelium-based composites?
2.3 How does the most optimal process looks like for growing mycelium-based composites?
2.4 What are the mechanical properties of mycelium-based composites consisting of these combinations and which combination perform best in terms of compression and three-point bending tests?

3. How can mycelium-based composite be designed and manufactured for a complex geometry building block for internal partitions?

1.4 Approach and Methodology

1.4.1 Method description

The project can be divided into three main phases: material research, improvement of mechanical properties (experimentation) and the design of the prototype made out of mycelium-based composites integrated into building elements.

Phase 1: Material research

- Literature study;
- Reference study / case study;
- Interviews with experts.

This phase took place between the P1 and P2. After P2, the literature review is partly finalized, with the possibility of incorporating minor changes and additions.

Phase 2: Optimizing the mechanical properties

- Experimentation;
- Reference study / case study;
- Interviews with experts.

This phase started after P2 and took place until P3.

Phase 3: Design

- Reference study;
- Experimentation (prototype testing);
- Interviews with experts.

In this final phase, a number of experiments were conducted to ensure optimal outcomes for the prototype and to evaluate the effectiveness of the composition.

1.4.2 Research by literature review

Part 1 mainly consists of literature research and interviews with experts. This research is the initial part of the thesis, gathering background information that will be used as a basis for the experiments that will be carried out in part 2. This part will include all the necessary information about the material, the growing process, advantages and limitations. It will help to launch the experimental phase. The outcomes of the experiments completed in phase 2 will have a significant impact on the design of the panel in phase 3.

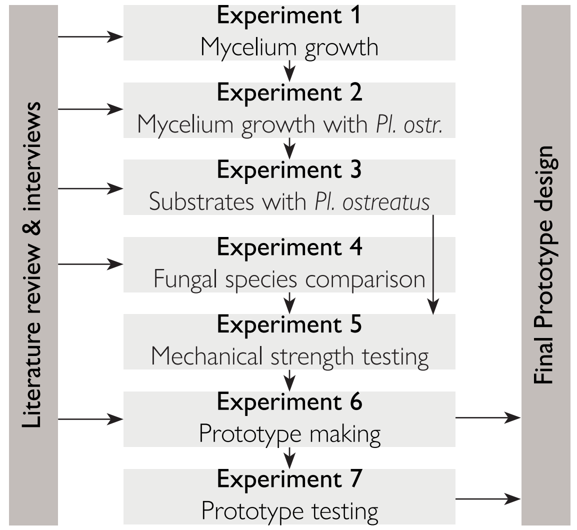


Figure 1. Methodology, own work

1.4.3 Experimentation schedule description

1. Mycelium growth
During this first experiment, mycelium-based composite from the Grow It Yourself kit will be grown. The substrate+mycelium used is confidential, so this experiment is to gain a deeper understanding of the material, the growing process, and the optimal environmental conditions.

2. Mycelium growth with *Pleurotus ostreatus* | Three methods
The stem butt method, whole mushroom strips method and grain spawn method are tested to see which part of the same mushroom *(Pleurotus ostreatus)* grows best on the same substrate (cardboard).

3. Substrates comparison with *Pleurotus ostreatus*
The most promising substrates based on literature and interviews with experts will be tested with the same fungal species, to test which substrates are most promising for the next experiments.

4. Fungal species comparison *Pleurotus ostreatus* vs *Ganoderma lucidum*
Pleurotus ostreatus and *Ganoderma lucidum* will be cultivated on the same most promising substrates in order to compare these species with each other.

5. Mechanical strength testing
The compression and three-point bending tests are undertaken for the purpose of facilitating a comparison of the results with one another and with the results observed in other building materials.
6. Prototype making
The first three variants of the prototype will be grown in the desired composition of materials.

7. Mechanical strength testing of prototype
This experiment is similar to Experiment 5, but with samples of the prototype composition, in order to ascertain whether this composition results in improved outcomes in comparison to the samples from Experiment 5.

1.5 Planning and Organization

The figure on the next page (p. 12 and 13) presents an overview of the general planning for the graduation process, from the initial stage (P1) onwards.

This research is being conducted on behalf of the TU Delft. This thesis forms part of the Master's track Building Technology within the MSc. Architecture, Urbanism and Building Sciences. For this track, two research fields must be selected: Building Product Innovation and Structural Design & Mechanics are selected within this thesis. Consequently, the research will be conducted under the guidance of experts in these fields: The first mentor is Olga Ioannou from the Chair of Building Product Innovation, and the second mentor is Mauro Overend from the Chair of Structural Design & Mechanics. The third supervisor is Nader Merhi from the company Witteveen+Bos, specialized in the field of Building Physics & Circularity.

1.6 Relevance

Nowadays, material scarcity is a growing concern and CO2 emissions and a circular economy has also become an increasingly prominent point of discussion. The use of traditional construction building materials with a linear process and high CO2 emissions makes these problems worse. Research into bio-based alternatives to current building materials is crucial.

From a scientific perspective, this research can make a significant contribution to the material studies of bio-based materials, particularly mycelium-based composites, given that these properties remain poorly understood. It will also improve our understanding of how to design with a relatively new material, the transformation of raw bio-based materials into a building product, and the calculation and experimentation necessary to ascertain the mechanical properties' suitability for building elements.

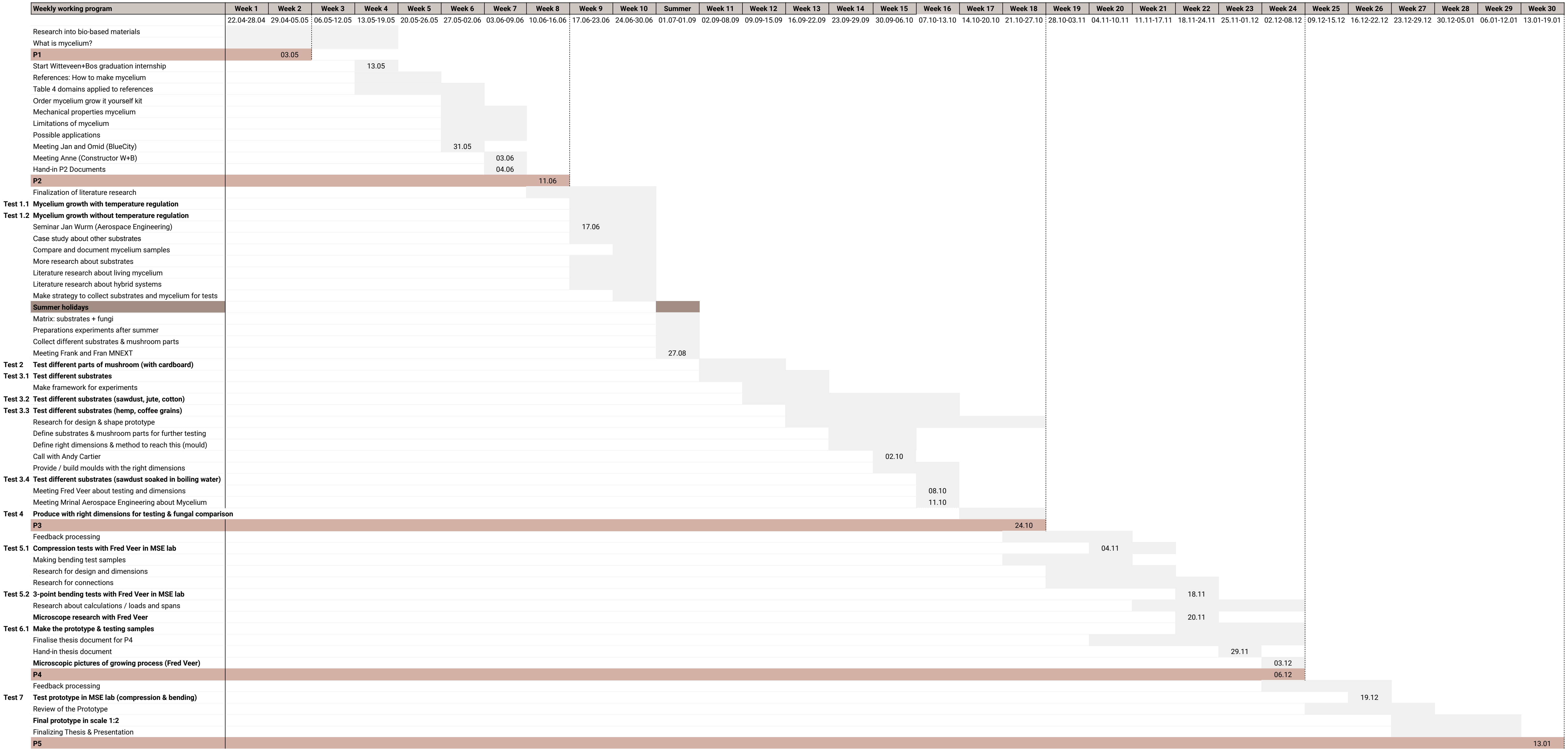


Figure 2. Time Schedule, own work

02
Background research

" What is a mycelium-based composite?"

02 Background Research

2.1 Mycelium & mycelium-based composites

"How are mycelium-based composites produced?"

"Mycelium" is the name for the root-like part of fungi (Figure 3). It is made up of long, branching threads called hyphae. These so-called hyphae are up to 10 µm in diameter, several cm long and form an interconnected network called mycelium (Wösten et al., 2018). The enzymes released by these organisms break down complex materials into simpler, more absorbable nutrients. This process creates an organic network of hyphae, which bind with the organic matter to form a fungal network. When mixed with a fiberous substrate, this becomes mycelium-based composite (MBC). In MBC, the substrate is the filler, and the hyphae (mycelium) acts as the binder. Without the hyphae, the substrate would just be a loose mass of particles with poor strength. So, the hyphae are essential for holding the material together (Ghazvinian & Gürsoy, 2022).

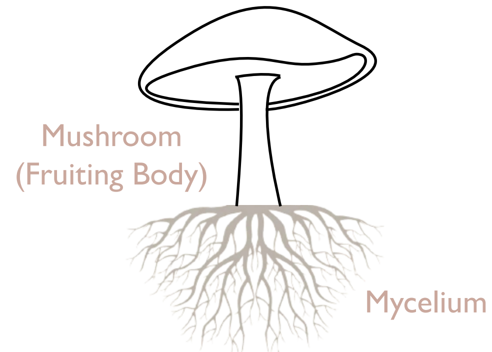


Figure 3. Mycelium, own work

2.1.1 The difference between mycelium and mycelium-based composite

In pure mycelium, the mycelium is grown on a substrate, which usually consists of organic material such as grains, soil, hemp fibers, straw, sawdust, or a similar material. During the growth process, the fungal threads (mycelium) are allowed to completely eat the nutrients in which it grows, breaking down the organic material and forming a solid network (Wösten et al., 2018). The resulting material consists mainly of the mycelium network, along with the substrate on which it is grown. No additional reinforcing materials are added (Ghazvinian & Gürsoy, 2022). The main limitation is that this process is relatively slow and the output is relatively low (Wörsten et al., 2018).

In mycelium-based composites, the mycelium is also grown on a substrate of organic material. However, in addition to this substrate, additional reinforcing materials are added, such as wood chips, straw, sawdust, textile fibers, or other natural fibers or materials. These reinforcing materials are mixed with the mycelium-mixture to form a composite material that combines both the properties of the mycelium and those of the reinforcing materials. Forming a three-dimensional network that binds the feedstock into a lightweight material (Elsacker et al., 2019).

The result is a material that can be stronger and more durable than pure mycelium, due to the incorporation of additional fibers. The formation of entangled networks by fungal hyphae bonding to the substrate results in improved mechanical strength in these composites. (Saez et al., 2022).

2.1.2 Growing process

The process of growing mycelium products is quite fast, but requires some points of awareness to make it work (figure 4):

0. The mycelium is initially cultivated on petri dished containing agar, in granular substrate, in liquid nutrient solution or in a pre-grown homogenised substrate;
1. The substrate and all tools and surfaces are sterilised to eliminate all types of micro-organisms already present on the equipment used to avoid contamination during the process of growth and incubation;
2. The mycelium is added to the substrate (10 - 20% of the volume of the substrate). If the substrate is not moistened during the sterilisation phase (step 2), a bit of sterile water is added. A solution of nutrients such as flour may also be added to enhance growth;
3. The inoculated substrate is then placed into a sterilised mould of the selected shape. The mould is covered with a air-permeable foil to maintain a microclimate;
4. The mycelium grows and develops through the substrate in a regulated environment. The material can be cultivated in two phases: initially within the mould to bind the fibres, and subsequently outside the mould to solidify the external layer of the material for a period of time;
5. The resulting material is heat-treated at a specified temperature for an extended period (see Figure 6 on the next page) to complete the growth process and facilitate the drying of the material;
6. In some cases, a coating or post-treatment may be applied to the material to enhance its properties.

(Vanden Elsacker & Vrije Universiteit Brussel, 2021)

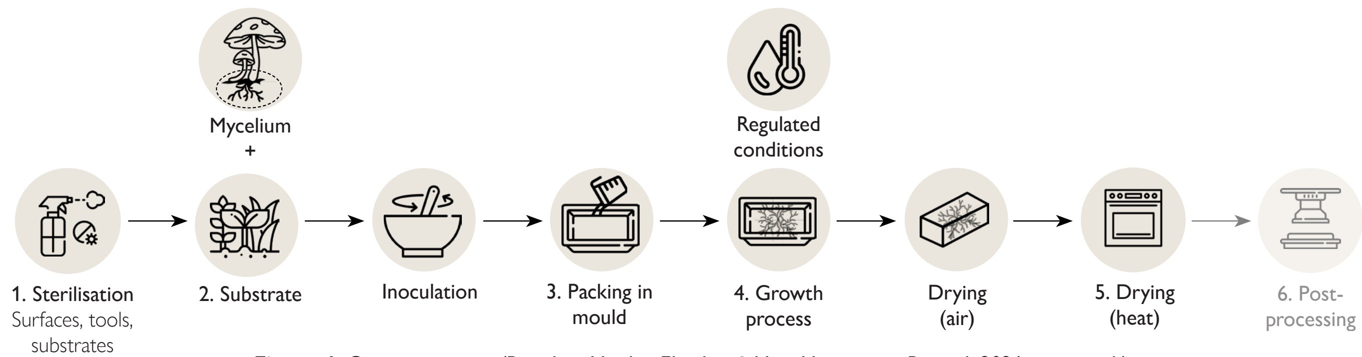


Figure 4. Growing process (Based on Vanden Elsacker & Vrije Universiteit Brussel, 2021, own work)

In order to prevent the contamination of the process by other bacteria, it is of significant importance to desinfect all items that may come into contact with the material, including the substrate, surfaces, and tools (Figure 5.1).

The fungal threads develop into a solid mass within a few days. Due to its processing method, mycelium can be grown into almost any shape by using a breathable mould that allows oxygen to reach the center of the material during growth. If no oxygen can reach the centre, the maximum thickness will be limited and the fungal threads dies (Dessi-Olive, 2022).

The growing proces requires a controlled environment with termperatures maintained between 24°C – 26° C. In the BlueCity in Rotterdam, they use a small cabin with temperature control (Figure 5.2). There are two small cabins for fewer or smaller product design and there is a larger one for larger scale production. (Appendix 8.1, row 4.4.2)

The baking time can vary from a few hours to a few days, depending on the size of the product (Appendix 8.1, row 4.4.3) and depending on the desired sample behaviour (Figure 6). Ovens of various sizes are used to accommodate different production scales. Figure 5.3 shows a smaller sized oven for material production.

2.1.3 Substrates

A substrate is defined as the material or surface on which an organism lives, grows, or feeds (Lelivelt, 2015). According to a study of Dessi-Olive (2022a), the combination of mycelium hyphae and fibrous substrates results in varying structural solidity, density, thermal conductivity, moisture resistance, and visual quality. It can be observed that a wide variety of materials with fibers can be employed as a substrate for mycelium. At the BlueCity, weed is the primary substrate employed for mycelium cultivation, due to its rapid growth and capacity to be stocked in large quantities (see Appendix 8.1, row 4.3).

In addition to the previously mentioned substrates, other materials commonly employed in reference projects, including Hy-Fi, Mycotree and Monolito Micelio, include hemp, corn stalks, sawdust, coffee grains, and sugar cane with cassava root (Almpani-Lekka et al., 2021).

Figure 5. Different stages of the growing process with the used tools (BlueCity, 2024)

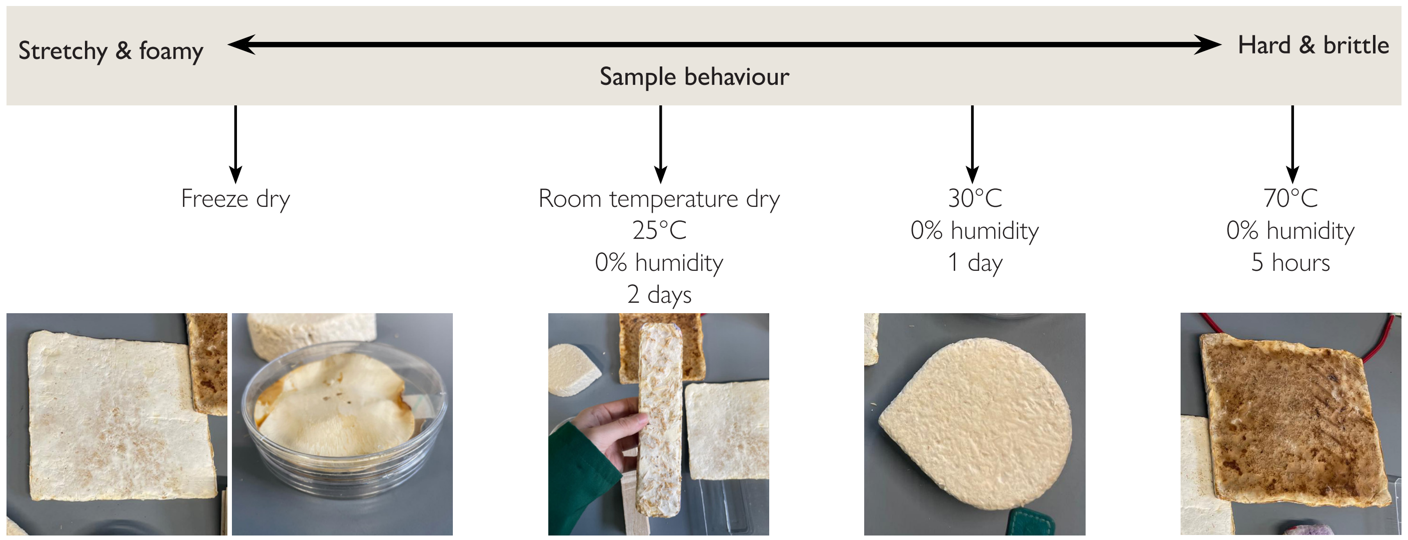


Figure 6. Different post-processing options for different sample behaviour (Based on interview and lab tour with Mrinal Chaudhury, Appendix 8.1.6, own work)

2.1.4 Advantages of mycelium

The bio-based material mycelium offers a number of advantages: it is lightweight, fire resistant, easily biodegradable or compostable at the end-of-life. Additionally, the production process generates minimal waste (Almpani-Lekka et al., 2022). Mycelium-based products offer excellent thermal and acoustic insulation properties and are CO2-negative when produced at a larger scale. The process is as follows:

1. The agricultural substrates have captured CO2;
2. These are then chopped, combined with mycelium and cultivated in moulds;
3. Lastly, these are transported;

These stages result in CO2 emissions, but the CO2 balance is negative when produced in large scale, due to the storage of additional CO2 in mycelium-based composites. (Mycelium Composites – Biobased Materials, 2023; Appendix 8.1.1, row 4.2)

In terms of production, a significant advantage of mycelium, compared to some other bio-based materials, is that it is a 100% bio-based material, requiring no specialized tools or machinery. Additionally, the material is highly versatile, allowing for a wide range of shapes and forms (Dessi-Olive, 2022a).

Figure 7. Advantages of mycelium, own work

2.1.5 Limitations

Mycelium-based composites offer several advantages for use in building elements. However, there are also some limitations to their applications. One of the main disadvantages of mycelium composites is their low mechanical strength (M. Jones et al., 2018). Despite the development of advanced processing techniques, mycelium-based materials still show poorer mechanical performance compared to traditional engineered composites made of materials such as glass or carbon fibers (Ibid.). This limits their widespread use in applications that require high load-bearing capacity.

Moreover, research has shown that monolithic mycelium structures require the use of either large scaffolds or extensive reinforcement systems in order to enhance their structural capabilities (Özdemir et al., 2022). In many cases, these reinforcement systems ultimately become the primary structural components, limiting the role of the mycelium to surface finishing rather than a primary load-bearing material. This limitation therefore represents a significant obstacle to the potential of mycelium-based composites to serve as stand-alone structural elements.

Also the lifespan of MBC is a topic of interest in academic literature. A review of literature indicates that mycelium bio-composites may have a shorter lifespan than traditional construction materials. This may result in the need for replacement one or multiple times during a building's 50-year operation (Livne et al., 2022).

In figure 8, the average lifespan of each building layer is presented, indicating the point at which the performance of the building elements included in this layer begins to deteriorate. The lifespan of the structure is set on approximately 30 - 300 years.

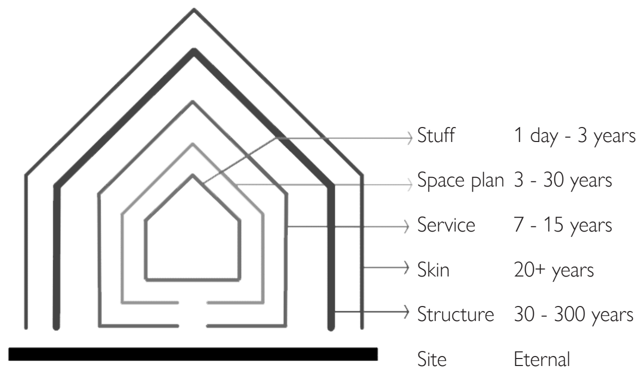


Figure 8. Layers of Brand and respective lifetime (Brand, 1995)

2.1.6 Lifecycle of mycelium composites

After the growing, drying and baking process, the mycelium composite brick can be integrated in a building component. In 2023, Alaux et al., assumed that the reference service life of Mycelium Based Composites (MBC) in building elements was set on 30 years, such as the other bio-based materials.

Mycelium-based composites are composed entirely of natural, biodegradable materials, as illustrated in Fig. 9. After soil composting, it is the ratio of mycelium to substrate and the materials themselves that will determine where the cycle goes. Furthermore, it would be beneficial to explore the potential of recycling the composites as a new substrate in the production of MBC (Alaux et al., 2023). This process involves recycling the composites into a new substrate. However, it remains unclear whether the substrate could consist entirely of waste mycelium, as some nutrients are consumed during the growth process. For the purposes of this analysis, Alaux et al. (2023) assumed that 70% of the MBC could be recycled as a substrate for a new one, with the remaining 30% requiring new substrate.

Compost time in soil: 45 days
Compost time in the ocean: 180 days.

2.1.7 Conclusion

Mycelium-based composites are produced through a bio-fabrication process that uses the natural growth of fungal mycelium to bind a fibrous substrate into a cohesive material. The process starts with the preparation and sterilisation of substrates such as sawdust, straw, or hemp fibres, which provide nutrients for the mycelium. Following this, the mycelium is inoculated into the substrate mixture, with a proportion of 10-20% of the total volume. The mixture is then packed into moulds of the preferred shape and allowed to grow under controlled environmental conditions, with a temperature range of 24-26°C. During this phase, the mycelium hyphae spread out, creating a dense network that binds the substrate into a solid composite. Following the completion of this phase, the material undergoes a drying process, which serves to end the mycelium growth and ensure the durability of the material. Depending on the intended application, post-processing treatments may be applied to enhance the material's properties, such as moisture resistance or structural strength. This innovative, sustainable process results in a lightweight, biodegradable material with minimal waste, which is suitable for a variety of applications, including use as an internal building element.

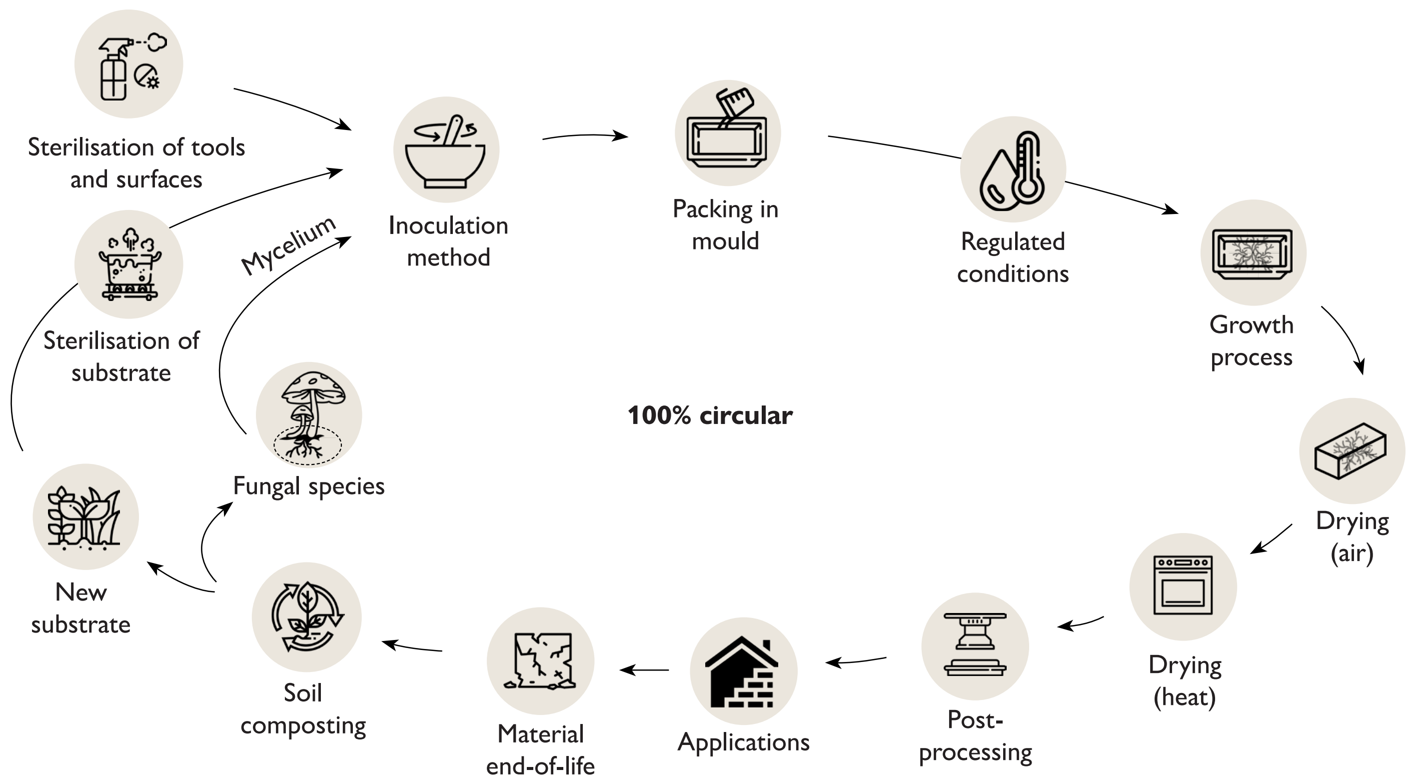


Figure 9. Life cycle assessment diagram mycelium-based composites (Based on Vanden Elsacker & Vrije Universiteit Brussel, 2021, own work)

2.2 Applications

" In what applications may mycelium-based composites be employed?"

The possible applications of mycelium-based composites are numerous. This chapter presents a review of existing studies that have employed MBC in different building applications, highlighting the utilisation of MBC's inherent properties, such as its acoustic and insulating characteristics.

2.2.1 References of application in structural building elements

Hy-Fi, New York 2014
The Hy-Fi design was created by the architectural firm The Living/D. The pavilion was constructed by Benjamin and Arup for the Museum of Modern Art (MoMA) PS1 in New York. Ecovative provided mycelium composite bricks, which were used in the same way as bricks in a masonry wall (Dessi-Olive, 2022a). The substrate used is corn stalks. Approximately 10,000 of these blocks were used, which makes Hy-Fi the largest mycelium composite building project until nowadays. This project demonstrated the potential of using mycelium in both modular and traditional construction methods. The design of the pavilion consisted of a cluster of cylinders that provided shade and facilitated cooling through upward air movements. Openings between the bricks allowed for controlled ventilation (Almpani-Lekka et al., 2022).

Figure 10. Hy-Fi New York, 2014 (Sağlam & Özgünler, 2022a)

The structure was anchored to a foundation of hemp concrete bricks with reusable ground screws. Arup's structural analysis confirmed that the bricks could support their own weight at a height of 13 meters and withstand wind gusts of more than 160 km/h. To minimize movement in the wind, the supporting scaffolding boards of the formwork were held in place. After the exhibition, the bricks were shredded and distributed across the ground, where they decomposed within 60 days (Ibid.).

Tree column, London 2022
London-based Blast Studio has developed a method of 3D printing with living mycelium, creat-ing a column that can be harvesting mushrooms before being used as a structural building el-ement. The two-meter-high Tree Column has a ribbed, wavy design that suggests a tree trunk. This design was algorithmically designed to improve structural strength and optimize condi-tions for the growth of mycelium. (Blast Studio, 2020)

Figure 11. Mycelium 3D printing. (Blast Studio, 2020)

The column was created by mixing mycelium with shredded coffee cups collected in London and feeding the mixture into a custom-made cold extruder, similar to a clay 3D printer. Once printed, the mycelium consumes the pulp from the coffee cups and grows through the column, producing mushrooms that can be harvested. The mycelium is then dried, creating a strong, insulating and fire-resistant building material. (Hahn, 2022)

The production process starts by shredding and boiling paper coffee cups to create a sterile pulp, which is mixed with mycelium and natural pigments for colour. This mixture is 3D printed layer by layer into modules that are stacked (Blast Studio, 2020). The design includes folds and slits that allow moisture and support mycelium growth by creating sheltered microclimates. After three to four weeks in a humid environment similar to a greenhouse, the column is dried at 80°C to stop mycelium growth and solidify the material. The resulting structure is light and strong, with properties similar to MDF (medium-density fiberboard), making it a potential replacement for concrete in small buildings (Hahn, 2022).

Figure 12. Blast Studio 3D printed column (Blast Studio, 2022)

MycoTree, Zürich 2017

MycoTree is a self-supporting structure that was shown as an indoor installation at the Seoul Biennale for Architecture and Urbanism (Dessi-Olive, 2022a). This project uses mycelium composites with sugar cane and cassava root as substrate as a structural material, combined with digital fabrication and parametric design techniques. The design uses three-dimensional Graphic Statics, a method to create structures consisting of compression only. To address the material's low stiffness and control other forces other than compression, a connection system of bamboo plates and steel dowels was used. (Almpani-Lekka et al., 2022)

Figure 13. Perspective of the MycoTree structure (Teteris, 2017)

Monolito Micelio, Georgia 2020

Monolito Micelio was a large-scale mycelium structure grown from a one-tonne mycelium-stabilized hemp colony supplied by Ecovative. The project was part of a graduate research seminar at the Georgia Tech School of Architecture. The arched pavilion was designed to challenge the repetitive nature of brick and block-based mycofabrication methods, and was inspired by the construction principles of earlier structures. It demonstrated that myco-materials can adopt the fabrication techniques of in-situ concrete, such as traditional panel formwork and flexible fabric formwork. The pavilion highlighted the need for further research to discover new and innovative construction methods beyond traditional materials. (Dessi-Olive, 2022a)

The success of the project was associated with a number of failures that revealed areas for future research. A key problem was that myco materials, as part of a larger structure, are highly sensitive to expansion and contraction when exposed to external elements. This makes them unsuitable for long-term outdoor use, except in temporary structures with a short expected lifespan. Temperature variations and rainfall caused the material matrix of the Monolito Micelio to crack, rot and be affected by organisms, including potentially dangerous mould (bottom picture in figure 13). Moreover, the internal reinforcement materials were much stronger and stiffer than the myco-materials, which further contributed to the cracking and rotting of the structure. (Ibid.)

Figure 14. The Monolito Micelio (Dessi-Olive, 2022b)

La Parete Fungina, 2022

Mycelium-based wall panels present a challenge: growing the large continuous surface areas needed for traditional walls is nearly impossible due to size limitations. However, alternative products are being developed. The University of Virginia (UVA) and Kansas State University (KSU) have "La Parete Fungina". This wall is composed of large building blocks fused together and employs in-situ monolithic fabric with hemp as substrate. (Dessi-Olive, 2022a)

Additionally, "La Parete Fungina" incorporates vertical tubes and post-tensioning to increase the thickness and strength of the elements. This prototype used reusable casts, offering the potential for large-scale and low-waste production. However, structural testing has not yet been conducted. (Ibid.)

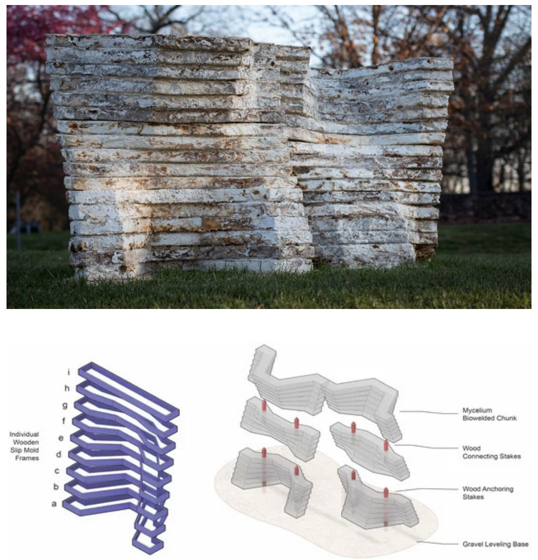


Figure 15. La Parete Fungina (Dessi-Olive, 2022d)

The living shelter, Floriade Almere 2022

This three meters high prototype of a biobased bus shelter is constructed from mycelium and represents a world first for the combined application of mycelium, wood and textiles. The mycelium is responsible for the growth of the shelter's components assembled together. The raw material for the mycelium is a residual stream from agriculture and horticulture. (Hartkamp, 2022)

Figure 16. Living Shelter - Mycelium Park (Hartkamp, 2022)

Shell Mycelium Pavilion, 2016

The pavilion was created by Studio Beetles 3.3 and Yassin Arredia Design for the 2016 Kochi-Muziris Biennale, which took place in the southwestern region of India. The objective was to construct a modular and lightweight structure that could be disassembled and transported for use in temporary events. The load-bearing structure was constructed using a wooden grid shell. The substrates were positioned within the cavities of each plywood frame, situated on top of the pavilion, and inoculated with mycelium (Almpani-Lekka et al., 2021). A notable aspect of this pavilion is the utilisation of a mycelium-substrate mixture that was not subjected to sterile conditions for its initial growth, but rather permitted to develop in an open-air setting. Additionally, the designers intended to allow the mycelial components to dry naturally by sunlight exposure. However, during the Biennale, a thin layer of mycelium began to cover the composite, yet the composite dried out naturally before binding fully. This project was an educational attempt at a non-discreet use of the mycelium composite, demonstrating the challenges associated with such an approach. (Ibid.)

Figure 17. Shell Mycelium Pavilion-2016 (Almpani-Lekka et al., 2021)

MycoKnit, 2021

In recent years, researchers have explored the potential of mycelium-based composites as load-bearing structural components in architectural applications. The production of knitted textiles is achieved by generating loops, or stitches, from a continuous thread, which is then iteratively moved through these stitches. The characteristic structure and forming process of these textiles result in multidirectional behaviour. Because of their flexibility and multidirectional properties, knitted textiles have been used in the development of seamless tension structures of varying complexity. Moreover, textiles, especially knitted materials, have been used as shuttering for fabrics such as concrete and resin, facilitating the creation of composite structural systems. (SOM Foundation, 2022)

This project holds significant importance for architects and designers, as it provides the possibility to create lightweight, large-scale shelters. It also has the potential to be completely biodegradable, aligning with sustainable design principles. Furthermore, the project contributes to reducing building waste, making it an innovative and eco-friendly solution for construction.

Figure 18. MycoKnit Tube Base Detail (Davis et al., 2021)

2.2.2 References of acoustic or insulating applications

Mogu, 2022
Mogu is a design company that specialises in the manufacture of sustainable and innovative products that are both aesthetically pleasing and technologically advanced. The company's products are derived from residual materials and by-products of other industrial sectors, and they represent a significant development in the field of mycelium-based products, being the first of their kind to be available on the market for interior design and architecture applications. Mogu's manufacturing processes are based on the principles of the Circular Economy, and as part of this, industrial waste materials such as cotton and hemp fibres are utilised. These materials are not able to be used for other valuable applications in textile production processes. (Mogu.bio, 2024)

Mogu's innovative technologies facilitate the creation of advanced solutions, establishing entirely new categories of products derived from environmentally sustainable processes rooted in mycelium technology and fermentation. A diverse range of nutrient-rich, low-value fibres from various industries (agro, textile, etc.) are utilised, and these are transformed through unique technologies based on fungal fermentation, adopting a fully circular approach. During this process, the mycelium serves as a reinforcing element within the substrate, leading to the formation of natural composite materials characterised by exceptional technical properties. These materials find application in diverse fields and offer significant potential for utilisation in a wide range of contexts. (Ibid.)

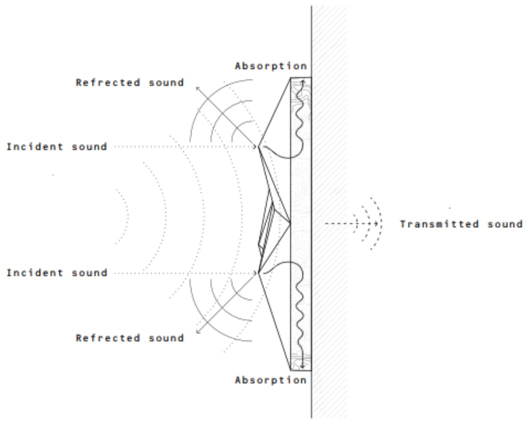
Mogu Acoustic panels are designed to offer dual mechanisms for sound correction: sound absorption and diffusion. The 3D-shaped surface of the panels has been engineered to break up and spread sound waves, while the porous mycelium material transforms them into micro-movement and heat. These vibrations are then absorbed by the fibrous material. It has been demonstrated that Mogu Acoustic panels exhibit excellent performance, particularly in the medium frequencies (250-1000 Hz). (Ibid.)

The panels are treated with a water-based, zero halogen, heavy metal- and solvent-free paint, which renders them naturally fire resilient due to the mycelium's capacity to slow down flame spread and form a char layer. Even without treatment, Mogu Acoustic panels undergo a slow carbonisation and burning process with a class D-s2-d0. However, an eco-friendly treatment has been applied to enhance their fire reaction to class B-s2-d0 (Ibid.).

Mogu further enhanced the panels with the incorporation of colours, thereby ensuring optimal aesthetic coherence when mixed and matched. The paint employed in this project is a water-based, heavy-metal-free bicomponent dispersion with low Volatile Organic Compounds (Ibid.)

Physical performance:

Quantity	Unity
Density	100 kg/m3
Flexural Strength	0,05 MPa
Compression Strength UNI EN 826	10,72 kPa
Fire Classification UNI EN 13501-2	B-s2-d0 (with treatment) D-s2-d0 (natural)
Thermal Conductivity UNI EN12664-2	0.045 W/mK (34 mm thickness)
Moisture sensitivity	RH > 50% (with treatment) RH > 80% (natural)
Frequency range	Medium (250 - 1000 Hz)



	t [mm]	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	NRC
Foresta	65	0,11	0,31	0,48	0,35	0,42	0,46	0,39
Wave	25-70	0,1	0,4	0,6	0,5	0,5	0,5	0,53
Plain	40	0,1	0,3	0,5	0,4	0,6	0,5	0,4
Kite	35-75	0,15	0,3	0,6	0,6	0,6	0,6	0,53
Fields	50	0,1	0,3	0,5	0,4	0,4	0,6	0,4

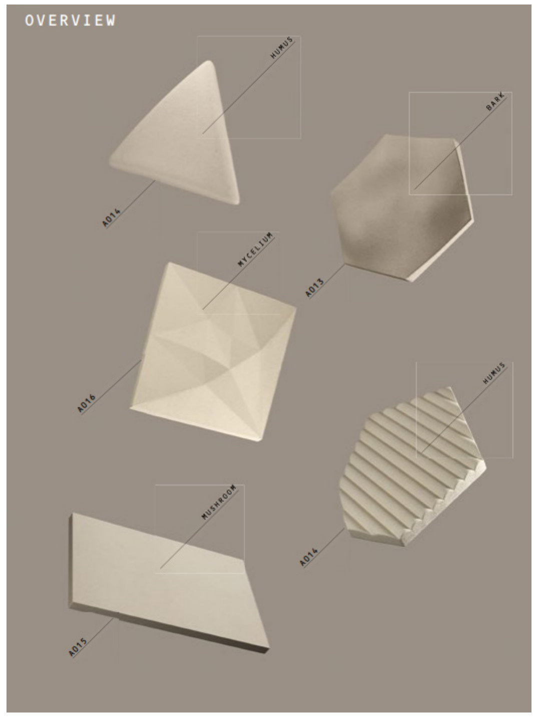


Figure 19. Mogu acoustic panels (Mogu.bio, 2024)

The properties of the various types of panels are dependent on their respective frequencies. The Kite panel is most effective in terms of sound absorption at lower frequencies, such as 250 Hz. However, at higher frequencies, the Wave panel demonstrates improved performance. It is noteworthy that the Kite panel has a higher thickness compared to other panels, which contributes to its superior sound absorption capabilities (Figure 19). The thickness of the material directly influences the effectiveness of sound absorption, with thicker materials providing greater benefits. This property is most advantageous at lower frequencies (Appendix 8.1.7, interview 2, row 4.1).

Myx Sail, Copenhagen, 2024
The Myx Sail represents one of the most significant structures created using Mycelium Textures, and is currently on display at the Danish Design Museum in Copenhagen. The Myx Sail absorbers are cultivated on a composition of several layers of plant fibers in combination with woven jute textiles with hemp mat and loose wood wool as a substrate. This results in enhanced mechanical and acoustic properties (Dwan et al., 2024).

The end substrate for the Myx Sail is a combination of materials: wood wool from pine trees (Pinus), a non-woven mat of hemp fibers and a Hessian textile of loosely woven jute fibers. The wood wool was selected for its lightweight and flexible composition, which enables it to keep its strength and position throughout the entire process. The hemp fiber mat selected as the optimal growing substrate due to its natural lignocellulose richness, which provides essential nutrients to support hyphal growth. The incorporation of a woven jute fabric serves to provide stability and strength, as well as assisting in the attachment of individual panels.

The fabric maintains the position of each panel in two dimensions, while enhancing flexibility and allowing for slight movement in the third dimension as the panels dry. During the installation process, the textile is positioned at the upper level to provide structural support for the suspension system from the ceiling. Meanwhile, the wood wool, which is more acoustically absorbent, is situated below the ceiling and faces the museum space. The additional mycelium was in the form of grain inoculated with spores of oyster mushroom (*Pleurotus ostreatus*), and the grains were incorporated between layers.

According to an additional survey conducted in the museum, the extent to which a grown surface (or, by extension, a grown building) is perceived positively or negatively depends on the relationship the individual visitor has with nature.

In Vivo, 2023
For the Venice Biennale 2023, Wallonia selected an interdisciplinary team comprising Bento and Vinciane Despret. The team has noted that the manner in which we produce (building) materials urgently needs to change, and they are exploring the possibility of creating building materials based on fungi (mycelium). The research, entitled 'IN VIVO', explores the concept of a 'living city' and is a call to action to transcend the boundaries between languages and disciplines. Bento's research is interdisciplinary, encompassing architecture, art and design, and explores the potential of mycelium. In the central chamber, the organisers employ natural, living materials, experimenting with the installation of panels of mycelium in a spectacular wooden structure (measuring 12m in length, 6m in width and 6m in height) and resting on a floor of raw earth from excavated soil. (Belgian Pavilion | in Vivo, 2023)

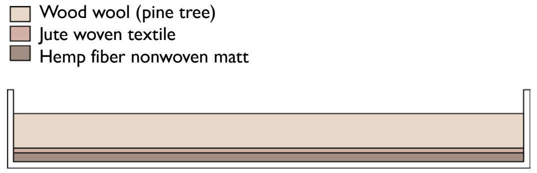


Figure 20. Setup, close-up and layers built-up diagram of the Myx Sail (Dwan et al., 2024)

Figure 21. In Vivo: The Belgian Pavilion (Belgian Pavilion | in Vivo, 2023)

2.2.5 The circular building product canvas

1. Material choice
2. Design
3. Manufacture
4. Management

(Circularity for Educators, 2024)

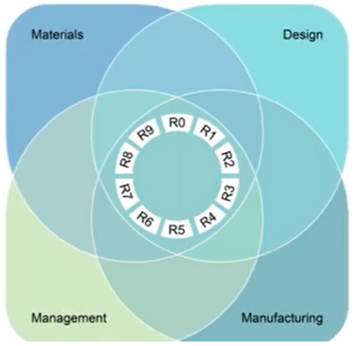


Figure 22. Circular Building Product Canvas (Circularity for Educators, 2024)

The circular building product canvas applied to Hy-Fi, New York (Benjamin, n.d.)

1. Material choice:
All materials at local level. Everything within this project came from within a small radius: The factory in which the bricks were grown is to the north of New York, the corn stalks were from upstate New York, the compost was used in local community gardens and for planting trees in the city and the composting plant itself is just a few kilometres away from the site of Hy-Fi.

2. Design
The bricks are not demountable, since they were connected to each other with a mortar. So when they are removed from the structure, they will break.

3. Manufacture
The process of making the mycelium brick requires no energy or complicated operation. Also no waste or any by-products are produce during the process. After Hy-Fi was demolished, the bricks with the mortar were brought to a composting factory nearby. Those bricks can be easily be composed, and within a short time, the high-quality compost is produced, which can be used as soil conditioner.

4. Management
The structure of Hy-Fi was also there to test whether people would accept this new material or not. It generated great enthusiasm from the people visiting it;

> "Everybody wanted to touch a brick"
> – Benjamin (n.d.)

This new structure also showed how much is possible at local level.

2.2.6 Conclusion

Mycelium-based composites have a variety of applications in the field of not-load bearing construction and design, due to their unique properties including biodegradability, lightweight structure and thermal or acoustic insulation. These materials have been used to create modular structures in architectural projects, for example the Myco-Fi pavilion in New York, which was constructed using mycelium bricks as building elements. Other notable applications include 3D-printed columns, such as the Tree Column in London, which integrates structural use with mushroom cultivation, and self-supporting structures, such as the MycoTree, which applies parametric design and mycelium's compressive strength.

Additionally, mycelium-based composites are increasingly used for acoustic and thermal insulation panels, providing sustainable alternatives to conventional materials. For instance, companies such as Mogu have developed panels for sound absorption and diffusion, illustrating the versatility of these materials in interior design. Furthermore, prototypes such as the Living Shelter at Floriade Almere demonstrate the potential for using mycelium in biobased shelters and lightweight modular components.

In conclusion, mycelium-based composites have the potential to be used in a variety of applications, including non-load-bearing structural applications, acoustic and thermal insulation, and innovative design projects. These composites offer eco-friendly solutions that align with the principles of sustainability and circularity.

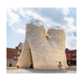
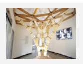
	Reference project	Type	Materials: Structure	Materials: Fungus	Materials: Substrate	Design	Manufacture	Management	Source
	**Hy-Fi (2014)**	Bricks	Wood & Steel	Ganoderma lucidum	Corn stalk waste	Prefab bricks	Heat treated	Stakeholders: The Living, D. Benjamin, Arup and Ecovative. Visitors of the MoMa PS1 Art Museum in New York	(Almpani-Lekka et al., 2021)
	**Mycotree (2017)**	Blocks	Bamboo & Steel	Pleurotus ostreatus	Sugar cane & Cassave root	Prefab bricks	Heat treated	Stakeholders: Visitors of the Seoul Biennale for Architecture and Urbanism	(Almpani-Lekka et al., 2021)
	**Monolito Micelio (2020)**	Monolith	Wood & Steel	Ganoderma lucidum	Hemp	Made in-situ	Naturally dried	Stakeholders: Ecovative, Georgia Tech School of Architecure	(Almpani-Lekka et al., 2021)
	**Tree column (2020)**	Column out of 10 modules	-	Mycelium (?)	Waste coffee cups	3D printed	Shredding and boiling coffee cups, naturally dried	Stakeholders: Blast Studio	(Blast Studio, 2020)
	**La Parete Fungina (2022)**	Panels into wall	Wood	Mycelium (?)	Hemp	Made in-situ	Large layers fused together with wooden reinforcement	Stakeholders: University of Virginia (UVA) and Kansas State University (KSU)	(David Alf, 2022)

Figure 23. 4 Domains applied to references, own work

2.3 Mechanical properties

"What are the advantages and disadvantages of using mycelium-based composites in sustainable building elements?"

2.3.1. Mechanical and physical properties

In the research of Alemu et al. in 2022 three substrates are used: sawdust (SD), coffee husk (CH) and bagasse (Bg). The fungus *Pleurotus ostreatus* (the oyster mushroom) was also used to produce a mycelium block (Mycoblock). *Pleurotus* species are widely used and studied by various scientists for mycoblock applications, followed by Trametes and *Ganoderma* due to their resistance to infection and faster growth than other fungal species (Ghazvinian & Gürsoy, 2022, p. 37-69). Hot pressing this block changes the property from foam-like to wood-like by improving their stifness and uniformity (Ibid.). The mycelium block made out of sawdust as substrate with a moulding time of 21 days has the highest compressive strength (750kPa) and the highest density of 343.44 kg/m3, compared with coffee husk and bagasse (Alemu et al., 2022).

The most important physical requirement for a traditional building brick is its great compressive strength of around 8,6 to 17,2 MPa. To date, there are no known research studies yet in which such great strengths have been reached with mycelium-based materials, which usually have a compressive strength of around 0,5 MPa. (Wösten et al., 2018)

2.3.2 Humidity

Mycelium is rich in water (over 60%) after the natural growth process. To inactivate the growth and achieve higher and more reliable mechanical performance, most of the water must be removed (Elsacker et al, 2019). This is done by baking the sample. In the available literature, the final percentage of moisture in the MBC sample is not specified.

2.3.3 Acoustic and insulating values

Furthermore, mycelium-based acoustic products demonstrate effective thermal insulation properties, with a thermal conductivity of 0.05 W/mK. This makes them a potential alternative to polystyrene (0.03–0.04 W/mK) and polyurethane (0.006–0.18 W/mK) foams (Vanden Elsacker & Vrije Universiteit Brussel, 2021). Also mycelium-based composites perform particularly well in the medium-frequency range (250–1000 Hz), which is where many human voices and environmental sounds fall (Mogu.bio, 2024).

2.3.4 Self-healing building material

The drying of mycelium-based elements results in the destruction of the organism through the application of heat, which in turn eliminates vital biological functionalities, including the capacity for regeneration. This section further examines the potential for maintaining the mycelium in a living state throughout the manufacturing process. (Vanden Elsacker & Vrije Universiteit Brussel, 2021)

Living building elements
Mycelial materials offer a number of additional advantages over traditional materials in terms of biological functionalities. These include the ability to self-heal damage or bridge voids while the material is still alive (Ibid.).

After being grown into form and after the hardening process of the mycelium, the process can be stopped by drying. The mycelium is then not alive anymore, but in theory it is possible to build with living elements. The components made out of the living material would be able to heal themselves. A crack in a building element, for example, would grow further and will be closed by itself. (Benjamin, n.d.)

The growing process would not be perceivable, but it could be possible to build even without mortar. The elements would grow together in a natural way. Maybe the elements still needs a small supply of nutrients during their lifespan to be able to keep continue the growing process. (Ibid.)

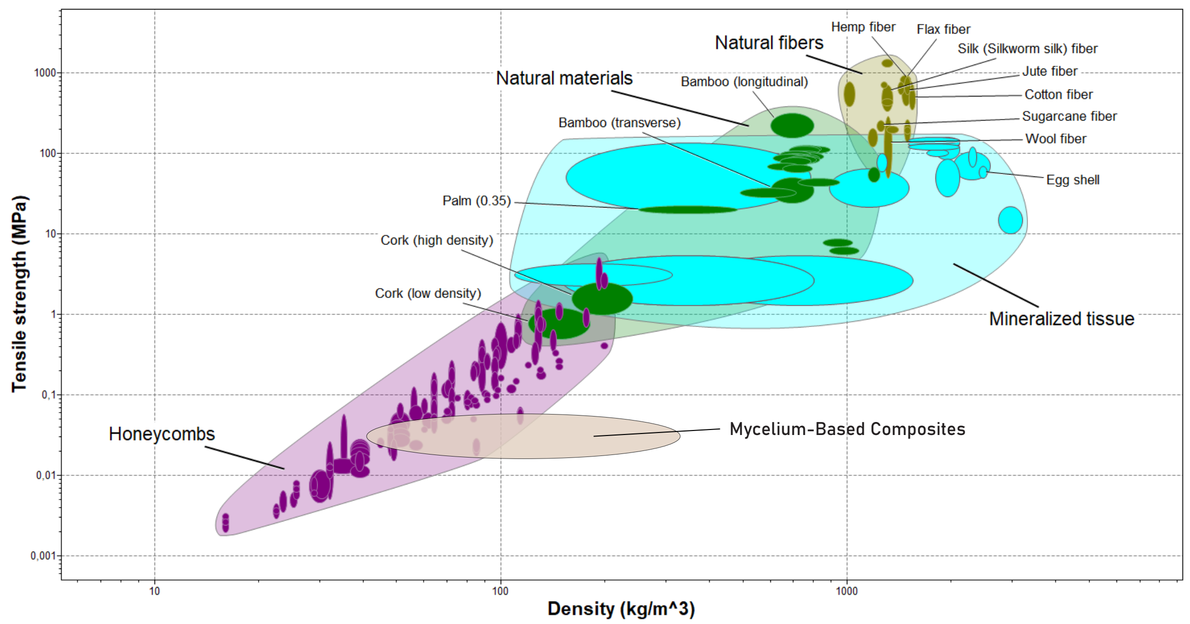


Figure 24. EduPack, plot of density vs tensile strength of natural, biobased materials against mycelium composites (Based on information from: Jones et al., 2020), own work

		Mechanical properties			Physical properties		
	Material	Compressive strength [MPa]	Tensile Strength [MPa]	Young's modulus [GPa]	Density [kg/m^3]	Thermal conductivity [W/mK]	Source
Bio-based materials	Bamboo	60 - 99,9	160 - 319	15,1 - 19,9	602 - 797	0,185 - 0,196	Granta EduPack 2023
	Cardboard	41 - 55	23 - 51	3 - 8,9	480 - 860	0,05 - 0,1	Granta EduPack 2023
	Cork	1 - 2	1 - 2,5	0,025 - 0,05	160 - 240	0,04	Granta EduPack 2023
	Cotton	-	360 - 660	7 - 12	1,52e3 - 1,56e^3	0,04 - 0,05	Granta EduPack 2023
	Egg shell	180 - 200	50 - 70	19 - 30	2,4e3 - 2,53e^3	-	Granta EduPack 2023
	Flax fiber	-	750 - 940	27 - 80	1,42e3 - 1,52e^3	0,04 - 0,05	Granta EduPack 2023
	Hemp	-	550 - 890	55 - 70	1,47e3 - 1,51e^3	0,04 - 0,06	Granta EduPack 2023
	Jute fiber	-	400 - 770	17 - 55	1,44e3 - 1,52e^3	0,038 - 0,046	Granta EduPack 2023
	Palm fiber	-	143 - 263	9,3 - 13,3	1,48e3 - 1,5e^3	-	Granta EduPack 2023
	Sawdust oak (l, quercus spp.)	68,2 - 83,3	133 - 162	20,6 - 25,2	850 - 1,03e3	0,07 - 0,12	Granta EduPack 2023
	Sawdust oak (t, quercus spp.)	12,8 - 15,6	7,1 - 8,7	5 - 5.58	850 - 1,03e3	0,07 - 0,12	Granta EduPack 2023
	Silk	-	340 - 720	5 - 25	1,26e3 - 1,35e^3	0,04 - 0,05	Granta EduPack 2023
	Straw bale	0,16 - 0,48	0,01 - 0,02	5e-4 - 0,002	80 - 191	0,045 - 0,065	Granta EduPack 2023
	Sugarcane fiber	-	190 - 260	17,9 - 27,1	1,22e3 - 1,28e^3	0,048 - 0,05	Granta EduPack 2023
	Wool	-	50 - 290	2,3 - 5	1,28e3 - 1,34e^3	0,038 - 0,043	Granta EduPack 2023
Building materials	Concrete (insulating lightweight)	0,5 - 2,8	0,1 - 0,3	0,6 - 1,53	900 - 1,4e3	0,1 - 0,7	Granta EduPack 2023
	High density concrete	30,6 - 36,6	3,1 - 3,7	40,2 - 41,6	4,9e3 - 5,5e3	1,6 - 2,5	Granta EduPack 2023
	Low alloy steel, SAE 8630, cast, quenched & tempered	827 - 914	915 - 1,01e3	196 - 204	7,81e3 - 7,84e3	42 - 48	Granta EduPack 2023
	Stainless steel, austentic, AMST CH-10, cast, water quenched	333 - 363	547 - 667	189 - 197	7,67e3 - 7,77e3	14 - 16	Granta EduPack 2023
	Timber: oak (l, quercus spp.)	68,2 - 83,3	133 - 162	20,6 - 25,2	850 - 1,03e3	0,16 - 0,2	Granta EduPack 2023
	Timber: oak (t, quercus spp.)	12,8 - 15,6	7,1 - 8,7	5 - 5.58	850 - 1,03e3	0,16 - 0,2	Granta EduPack 2023
	Mycelium-based composites	0,17 - 1,1	0,03 - 0,18	0,05e-3 - 0,29e-3*	59 - 552	0,05	(Jones et al., 2020)

Figure 25. Mechanical and physical properties MBC, bio-based materials and traditional building materials, own work

* = Flexural strength
l = longitudinal
t = transverse

Bio-welding components
After the cutting of the threads, the living component was reassembled by Vanden Elsacker & Vrije Universiteit Brussel in 2021 through the formation of a connection between two cut elements and the stimulation of regeneration of the outer mycelium skin. The two separate components were assembled together in an incubation chamber maintained at a temperature of 26 °C and a relative humidity of 90%. Additional humidity was required, as the sample underwent dehydration during the cutting and transportation processes. An increase in the humidity level permitted the hyphae to continue their growth by extending the ends and bridging a 5 mm gap between the two elements.

As the organism continued to grow, it produced a dense network around the exposed fibers of the substrate. The mycelium then aggregated on the substrate, undergoing differentiation to form a well-isolated brown-grey skin. After three days, the growth rate slowed significantly. The two different parts were fully connected after seven days. Finally, the whole block was air-dried in an incubator chamber at 30°C for a week and remained solid. (Vanden Elsacker & Vrije Universiteit Brussel, 2021)

2.3.5 Accelerated aging

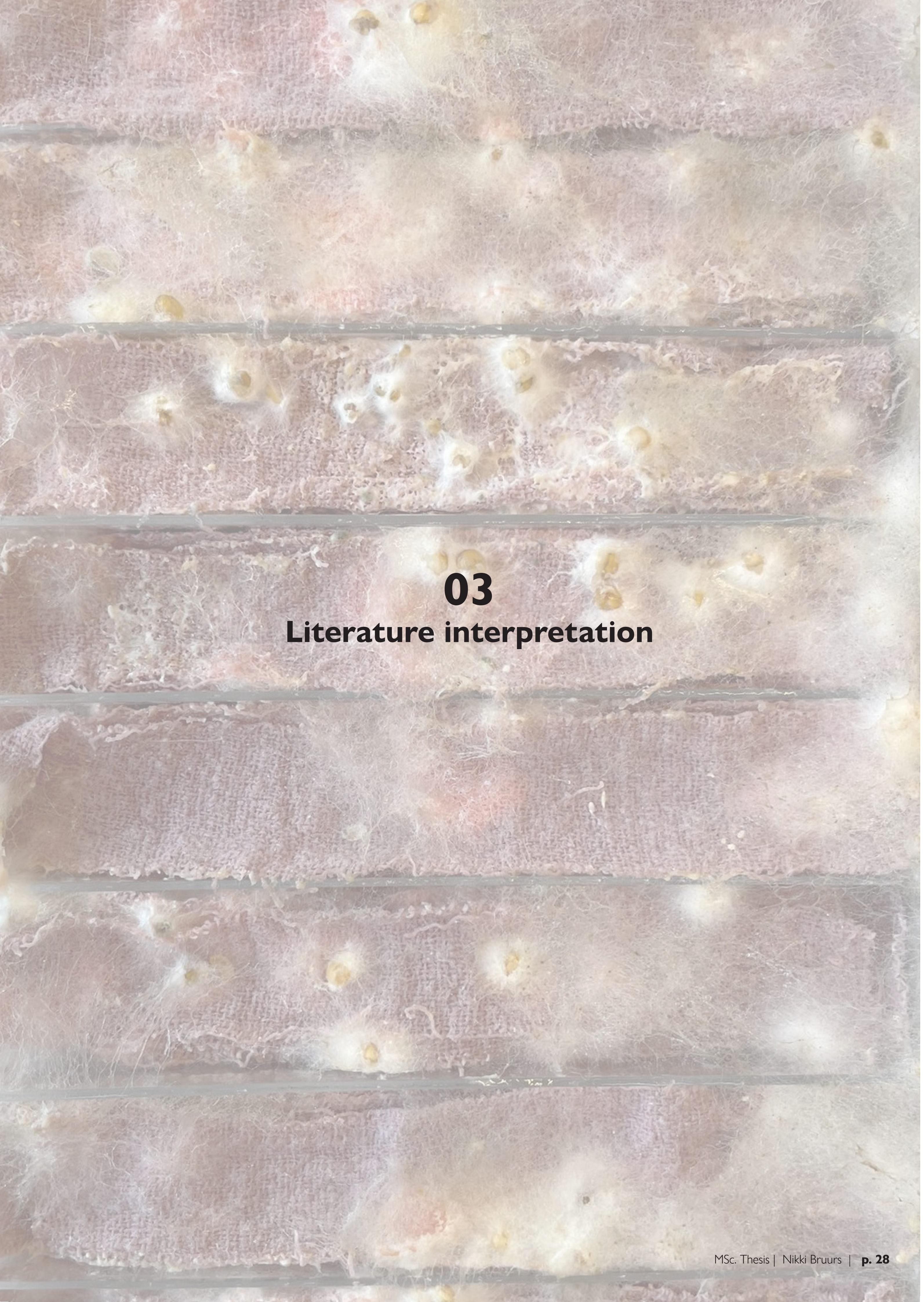
At the Hy-Fi building in New York, the architects did a study about the environmental conditions of the organic brick by using accelerated aging tests. This experiment simulated three years of exposure of the bricks to weather and wind gusts within three weeks. In a test chambre samples were subjected to temperature swings, moisture cycles and other environmental conditions. The results of the tests were very promising, because the different bricks showed no change of characteristics whatsoever after the accelerated tests of three years. Under real conditions the empirical values for aging have not been obtained yet. (Benjamin, n.d.)

2.3.6 Conclusion

Mycelium-based composites offer several advantages for sustainable building elements, mainly due to their lightweight structure, biodegradability, and thermal and acoustic insulation properties. They are 100% biobased, non-toxic, they have acoustic and insulating values and can be cultivated into numerous shapes with minimal waste generation during production. Moreover, mycelium-based composites are CO2-negative when produced on an industrial scale, as they absorb more CO2 than is released during their lifecycle. These characteristics make them suitable for applications that focus on sustainability and circular building practices.

However, mycelium-based composites face significant challenges that limit their wider application as structural building materials. One of the main disadvantages is their low mechanical strength, particularly in compression and bending, when compared to traditional construction materials like concrete or steel. Their limited durability and shorter lifespan also cause concerns, especially for long-term building use. While the addition of reinforcements and the optimisation of growth techniques can enhance the mechanical performance of MBC, they still face challenges in achieving the load-bearing capacities required for standalone structural elements.

In conclusion, mycelium-based composites show great potential for use in sustainable building elements due to their environmental benefits, their natural acoustic and insulating values and multifunctionality. However, their lower mechanical strength and durability emphasise the necessity for further research and innovation to expand their application beyond non-structural and temporary uses.



03
Literature interpretation

03. Literature interpretation

3.1 Mycelium selection

Three criteria for using a fungal species:

- Rate of growth;
- Strong connections (hyphae);
- Resistance to external mould contamination.

Three methods:
1. Stem Butt Method
2. Tear up the mushroom into small strips
3. Use grain spawn from the mushroom.

Pleurotus ostreatus
Following a review of the literature, it was evident that the *Pleurotus ostreatus* species represented a logical choice to use with the experiments, given its frequent use in numerous reference projects (Figure 26 on page 31).

Pleurotus ostreatus is an edible white rot fungus with the ability to break down cellulose. This makes it well-suited to grow on waste materials such as wood, textiles, and agricultural waste (Zhong et al., 2021).

Pleurotus species are also widely used and studied by various scientists for mycoblock applications, followed by Trametes and *Ganoderma* due to their resistance to infection and faster growth than other fungal species (Ghazvinian & Gürsoy, 2022, p. 37-69). This rapid growth is fundamental requirement for the experiments, given the limited timeframe of the graduation project.

Currently, *Pleurotus ostreatus* (Oyster mushroom) is also one of the most extensively produced edible mushrooms globally. Cultivation can be conducted on a diverse range of substrates, including cereal straw, sawdust, bagasse, cotton waste and hardwood. The optimal conditions for inoculating the substrate are a moderate temperature and humidity. The production of fruiting bodies depends on the environmental factors, including temperature and light. As a consequence of this knowledge, its use as a building material is made easier. (Moser et al., 2017).

Ganoderma lucidum
In addition to the literature review, several meetings were held during the course of this graduation project. During these meetings, it became evident that the *Ganoderma lucidum* species is currently a subject of considerable research interest.

This species is widely used in practice due to its capacity for more rapid growth and greater resilience to external mould. Additionally, it facilitates the formation of stronger mycelial networks (Appendix 8.1.5 & Appendix 8.1.6).

Pleurotus ostreatus
Grain spawn

Ganoderma lucidum
Hedelcomposite

It should be noted that the scale of the two images above is not identical. The grain spawn is contained within a 1 kg bag, whereas the hedelcomposite is present in a 10 kg (20 L) bag.

3.2 Substrate selection

Three criteria for using a substrate:


1. Enough cellulose for the fungi to feed on;


2. Mechanical strength;


3. Formability

Hemp fiber particles and Hemp fiber mat
Hemp has been utilised in Monolito Micelio (2020), La Parete Fungina (2022) and the Mogu acoustic panels. Furthermore, a hemp fibre mat was employed in a layer of the MyxSail in 2024 as the growing substrate, providing nutrients to support hyphal growth due to its natural lignocellulose richness. It is noteworthy that these references are all very recent.

Corn stalk waste (Corn granules)
Corn stalk waste is used at Hy-Fi (2014) in a brick shape, mostly because it was local waste stream. This project was the first large structure made of mycelium. For the experiments corn granules are used. The corn granule is composed of the core of the corn cob.

Coffee grain waste
This substrate is employed in the Frysl6an Fungies reference, from which the mycelium grain spawn is derived (for the purpose of cultivating mushrooms). It stands to reason that this substrate is conducive to the optimal growth of the spawn.

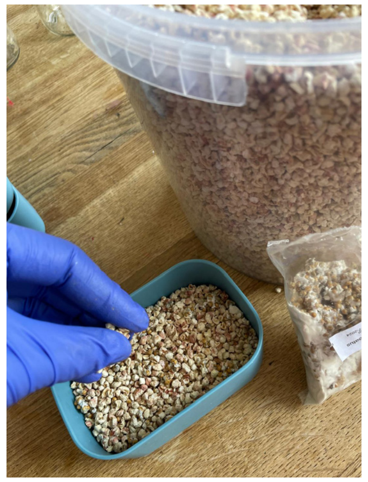
Cotton
Cotton has been selected for use as a substrate in the Mogu acoustic panels, indicating its potential as a material worthy of further investigation.

Jute
A woven jute fabric was used in one of the three layers of the MyxSail in 2024, providing stability and strength. It is also used to support the suspension of each panel and to maintain the position of the panels in two dimensions to improve flexibility and slight movement in the third dimension as the panels dry.

Oak Sawdust
The mycelium block, which was fabricated from sawdust as a substrate and underwent a moulding time of 21 days, has been shown to possess both the highest compressive strength and density when compared with coffee husk and bagasse (Alemu et al., 2022). Sawdust has been referenced in several other studies, which suggest that it is a promising material.

Flax fiber mat
Flax fibers are not used in any references, but they seem to have a good tensile strength, which could be useful for a building element (depending on the application).

Loose fibers	Woven	Granular
Hemp fiber mat	Cotton	Coffee grains
Flax fiber mat	Jute	Hemp fiber particles
		Sawdust



3.3 Material matrix, based on literature

Fungal species	Substrate	Application	Growth conditions and growing time	Usefull for tests?	Comments	Source
Pleurotus Ostreatus (stem butt)	Cardboard	Not specified, used for testing growing rate	Daylight, roomtemperature	Substrate is not flexible enough for complex shapes		(GroCycle, 2019)
Pleurotus Ostreatus (stem butt)	Hemp	Not specified, used for testing growing rate	Daylight, roomtemperature	Yes		(GroCycle, 2019)
Trametres hirsuta	Processed cellulose or straw	MBC boards		No	Hot pressed	(*Mycelium - MNEXT*, 2021)
Lenzites betulina	Processed cellulose	MBC boards		No	Hot pressed	(*Mycelium - MNEXT*, 2021)
Ganoderma resinaceum	Rapeseed straw or hemp shives	MBC foams		No		(*Mycelium - MNEXT*, 2021)
Lenzites betulina	Hemp fibres	MBC foams		No		(*Mycelium - MNEXT*, 2021)
Pleurotus ostreatus	Sugar cane & cassave root	MycoTree column made out of block components	Heat treated	No	Connection system of bamboo plates and steel dowels	(Almpani-Lekka et al., 2022)
Pleurotus ostreatus	Sawdust	Brick	21 days	Yes	Compressive strength: 750 kPa, Density: 343,44 kg/m3	(Ghazvinian & Gürsoy, 2022, p. 37-69) & (Alemu et al., 2022)
Pleurotus ostreatus	Sawdust	Brick		Yes	Hot pressed (properties from foam-like to wood-like)	(Ghazvinian & Gürsoy, 2022, p. 37-69)
Pleurotus ostreatus	Coffee husk	Brick		Yes		(Ghazvinian & Gürsoy, 2022, p. 37-69)
Pleurotus ostreatus	Bagasse	Brick		No		(Ghazvinian & Gürsoy, 2022, p. 37-69)
Not specified	Knitted fabric	Monolith structure (MykoKnit)		No, not specified fungal species	Tensile structure (cables and weights) during pouring process	(SOM Foundation, 2022)
Ganoderma lucidum	Hemp	Monolith structure (Monolito Micelio)	In situ, outdoor environment	Yes, but not with naturally grown and dried method	Unsuitable for long-term outdoor use, except in temporary structures with a short expected lifespan	(Dessi-Olive, 2022a)
Not specified	Residual stream from agriculture and horticulture	Bus shelter in components (The living shelter)		No, not specified fungal species	Wood and textiles used for reinforcement	(Hartkamp, 2022)
Pleurotus ostreatus	Different layers of plant fibres combining woven jute textile with hemp mat and loose wood wool (from pine trees)	Acoustic panel (MyxSail)		Yes	The woven jute textile was chosen to provide strength and stability and facilitate suspension of the individual panels	(Dwan et al., 2024).
Not specified	In-situ monolithic fabric with hemp	Blocks fused together (La Parete Fungina)		No, not specified mycelium species	Vertical tubes and post-tensioning to increase strength and thickness	(Dessi-Olive, 2022a)
Coriolus (T.) versicolor and Pleurotus Ostreatus	Hemp hurd, hemp fibres, hemp mat, wood chips, non-woven mats	Foam	Dark conditions, high room temperature, duration: 30 days. Dried for 2 days at 125 °C	No		(Lelivelt et al., 2015)
Pleurotus ostreatus and F. fomentarius	Wood chips (Beech, oak and spruce) of 0,2 - 5,0 mm and 0,75 - 3,5 mm with sand and gravel	Contruction material	25°C – 28°C for 14 – 28 days. Baked at 95 °C until it weighs ≤ 50% of its original weight	Yes		(Moser et al., 2017)
Ganoderma lucidum	Waste corn stalks	Brick for construction (Hy-Fi)	Heat treated	Yes	Anchored to a hemp concrete brick foundation with reusable ground screws. Also supporting scaffolding boards.	(Almpani-Lekka et al., 2022).
Not specified	Shredded coffee cups	Tree column	After 3-4 weeks in a humid environment similar to a greenhouse, the column is dried at 80°C	No, not specified mycelium species	3D printed. Properties similar to MDF (medium-density fibreboard)	(Hahn, 2022) & (Blast Studio, 2022)
Not specified, developed by Ecovative	Flax, jute, cellulous plain weave	Core of sandwich structure	Grown in 4 days in 24° C. Dried in a convection oven for 12 hours at 82°C and 8 hours at 93°C	No, not specified mycelium species	Thermally pressed and dried at 250°C for 20 minutes till the required thicknesses	(Jiang et al., 2017)
Fomes fomentarius	Hemp	Panel (MY-CO SPACE)	4 weeks of growing. Dried in 2 days in the oven at 60 °C	Yes	Wood and steel structure, heat treated and weather resistant coating	(Meyer, 2024)
Not specified	Coir pith	Panel (Shell Mycelium)	Naturally dried	No, naturally dried & not specified fungal species	Wood and steel structure	(Almpani-Lekka et al., 2022).
Not specified	Cotton and hemp fibers	Acoustic panels, wall panels		Yes	Excellent acoustic performance in the medium frequencies (250-1000 Hz).	(Mogu.bio, 2024)

Figure 26. Concluding material matrix, own work

04
Experimentation

"What different combinations of substrate and fungal species can be used to make mycelium-based composite suitable for sustainable elements?"

04 Experimentation

This chapter focuses on the question "What different combinations of substrate and fungal species can be used to make mycelium-based composites suitable for sustainable elements? This will be answered by conducting several experiments:

Experiment 1: Mycelium growth
Producing mycelium-based composite from the Grow It Yourself kit. The purpose of this experiment is to get to know the material , the environmental condition settings and the growing process.

Experiment 2: Mycelium growth with *Pleurotus ostreatus*
The stem butt method, whole mushroom strips method and grain spawn method are tested to see which part of the same mushroom grows best on the same substrate (cardboard).

Experiment 3: Substrates with *Pleurotus ostreatus*
The substrates that seems promising based on literature are hemp fiber particles, loose hemp fibers, coffee grains, oak sawdust, corn stalks, loose flax fibers, woven jute and woven cotton. Those substrates will be testen on growing rate and level of resistance to external mould contamination.

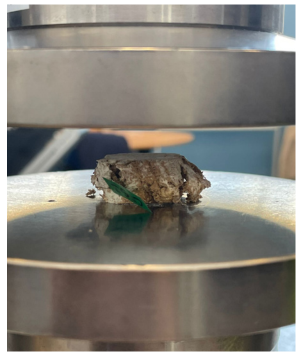
Experiment 4: Fungal species comparison
Pleurotus ostreatus* vs *Ganoderma lucidum
Cotton, jute, hemp fiber particles and oak sawdust will be growing on both *Pleurotus ostreatus* and *Ganoderma lucidum*, to be able to compare these species with each other. The criteria for a substrate are the rate of growth and resistance to external mould contamination.

Experiment 5: Mechanical strength testing
The compression and 3-point bending tests will be utilised at the MSE lab in the Mechanical Engineering faculty at the TU Delft. The outcome of the experiment will be the combination of fungi and substrate with the best results. This combination will be taken further to the next chapter: 05. Design.

Chapter 05 Design (p. 82):

Experiment 6: Prototype making
Make the prototype panels with 3 variants, including and all the needed components.

Experiment 7: Testing mechanical properties of prototype
Same experiment as experiment 5, but now with samples of the prototype composition.



4.1
Mycelium growth

4.1 Experiment 1 | Mycelium Growth

This experiment took place at The Faculty of Architecture, TU Delft, Room 01+.West.030, with help from Dr.ir. M.J. (Martin) Tenpierik. The hotbox, device and PCM used during this and all the coming experiments is also in possession of Martin Tenpierik.

4.1.1 Day 1 | Preparations

1. Hotbox
The temperature was set around 24°C – 26° C by trial and error with the LED lights. The app 'AranetHome' provides information about CO2, relative humidity, temperature, and atmospheric pressure when the device (iPhone) is close to the thermometer and connected through Bluetooth. Also the screen on the small device in the box will provide information about the circumstances at that specific moment.

2. Tools and the material
The initial step is to sterilise all tools and surfaces. This process is conducted using boiling water. The use of gloves ensures that the environment is maintained in a sterile state. Following the sterilisation of all materials, the mycelium and substrate are combined with the flour in a sterile bowl and thoroughly mixed.

3. Filling the mould
Also the mould is disinfected with boiling water.

Problem 1: The mould is made of plastic, so it deformed due to the boiling water.

Solution: (for the next time)
- Use another mould (not made out of plastic), or;
- Use ethanol instead of boiling water to disinfect, or;
- Leave the boiling water in the mould for only a very short period of time.

Subsequently, the mixture is to be placed within the mould. It is of importance to ensure that the corners are also adequately filled by applying slight pressure.

Problem 2: Because the hotbox was still occupied by another student when the growing process of the substrate + mycelium was actually supposed to start (within 5 days of receiving the package), the packed material already started to grow together. As a result, the material had to be taken apart before it could be put into the mould.

4. Cover
Once the mould has been filled, it must be covered with a plastic foil in order to prevent contamination. However, the plastic foil must have small holes in it in order to allow the mycelium to breathe.

5. Growing phase in the mould
The mycelium grows between 3 – 5 days at 24°C – 26° C in the hotbox;

Problem 3: The LED lights regulating the temperature inside the hotbox had to be turned off at the end of the day due to fire safety concerns.

Solution: PCM grains (Phase Changing Material) were added into the hotbox to add thermal mass so the temperature would stay more constant during the night.

Hotbox with 2 LED lights

All tools used: sterlisation process

Deformation of the mould

Left: The material had already begun to grow together;
Right: Plastic foil with holes over the material.

PCM for thermal mass

6. Mycelium growing at home (17:00h)
To check whether the mycelium actually needs the constant temperature of 24°C - 26°C to be able to grow, there is some mycelium + substrate left over to test at home. The same steps as above were fulfilled, except for the hotbox steps.

The temperature in the room was at daytime: 22,5 °C.
By night, the temperature decreased to 21,0 °C.

A disadvantage of the experiment conducted at home was the lack of precision in the registration of temperature and moisture levels. This was due to the unavailability of the device used at the TU Delft.

4.1.2 Day 5

1. Higher growing rate
Because the light has been turned on for the entire night after day 4 (seen in the temperature diagram at p. 38), there was more mycelium development. Also the moisture level has increased after the night. The sample has reached a sufficient level of development to be ready for the drying and baking process to commence.

2. Drying process
As detailed in the instructions provided with the Grow It Yourself kit, the material can be carefully removed from the mould once it has reached a fully white colouration. (Eileen, 2024)

Problem 4: As formulated in Problem 1, the mould was deformed as a consequence of the disinfection process, which involved the use of boiling water. This has resulted in the mycelium being unable to emerge from the mould. Attempts were made to demolish the mould in order to remove the sample, but the plastic mould was found to be too rigid.

The alternative mycelium product grown from home was available to take out of the mould and to dry for two more days to get a white skin.

After two days, the sample can be baked:

Sample thickness > 25 mm: pre-baking process at 40°C for 3-4 hours;
All samples: 80°C for two hours. (Eileen, 2024)

Temperature at home

Relative humidity and Carbon dioxide information from the Aranet Home app, placed in the hotbox


Moisture development under the foil


Broken sample because deformation of the mould


Drying and baking of the sample grown at home

4.1.3 After one month

The difference between the baked sample and the living sample in the mould was visible after one month. The baked one had still the same visual characteristics, but the living sample had a new small mushroom grown on the side, shown in the figure right.External mould had also developed at the bottom of the sample, and the mycelium did expand more, as seen by the expansion of the white part in the figure right. The cracks were still present, indicating that the mycelium was not healing itself without the addition of nutrients.

Growing process

Hotbox TU Delft | At home

Day 1
Day 2
Day 3
Day 4
Day 5

After one month

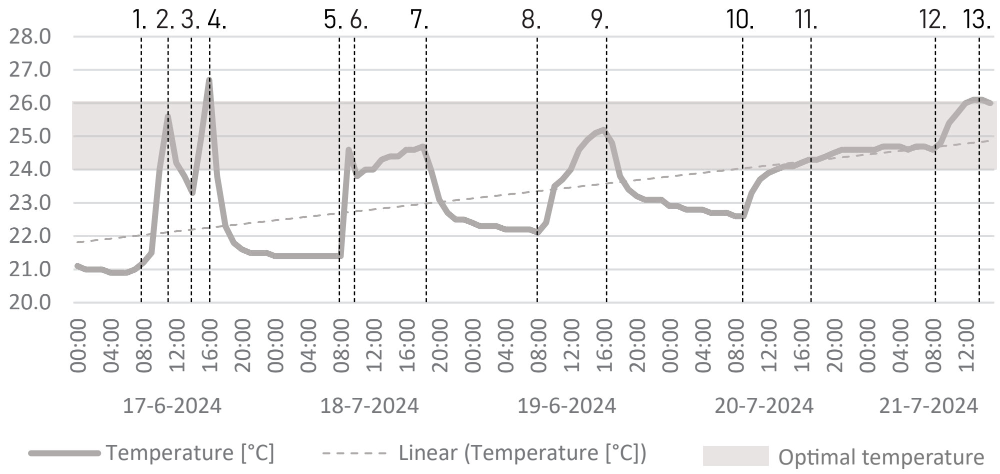


Figure 27. Temperature diagram during experiment 1 (Based on information provided from the app 'AranetHome', own work)

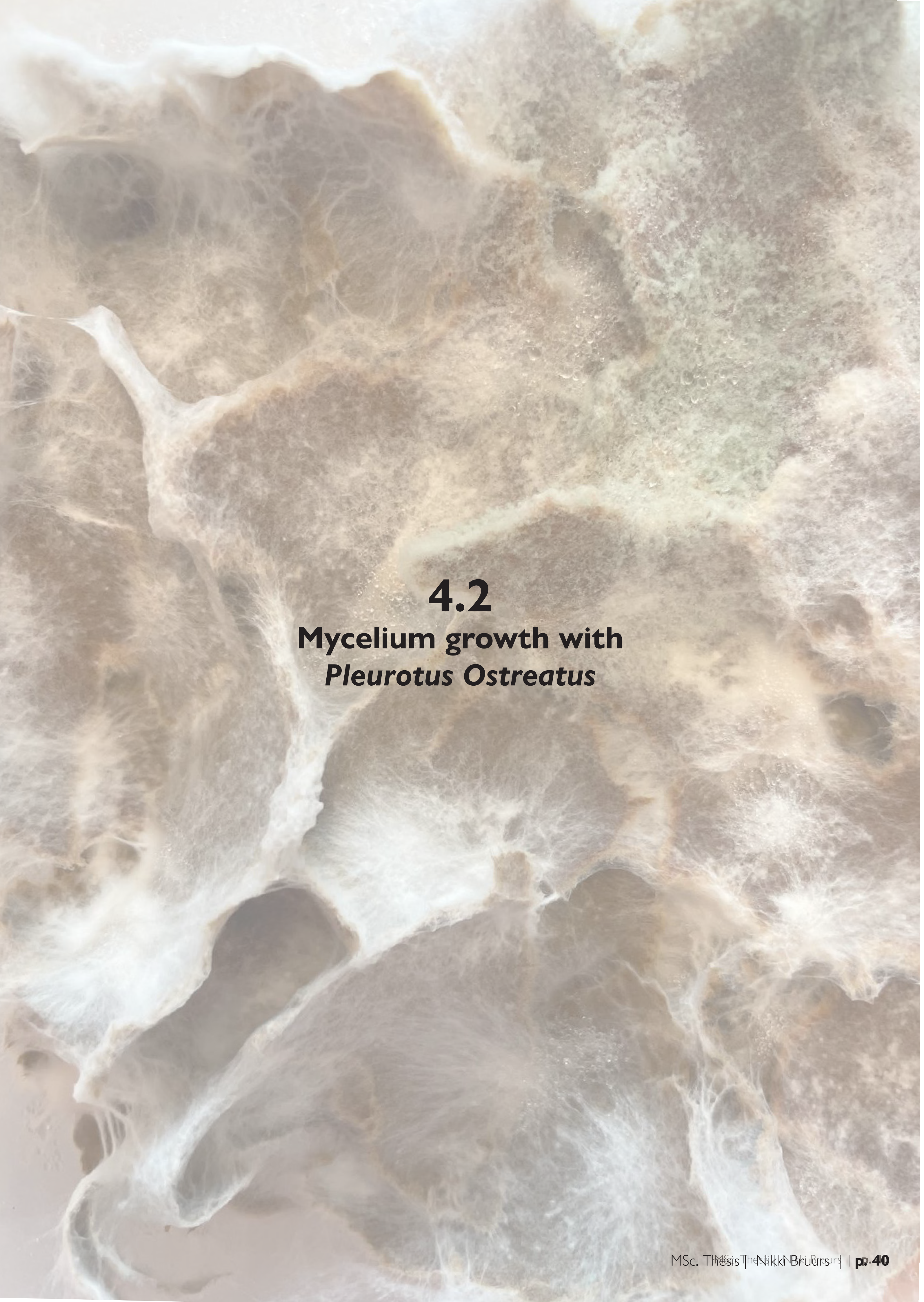
4.1.4 Temperature diagram

At the start of the experiment, the process to find the right temperature was trial and error, using different LED lights and additional thermal mass. The temperature dropped sometimes because the opening of the hotbox was opened to make pictures or at night because the heat source was switched off. As the thermal mass was heated more and more, the temperature difference between day and night became smaller.

1. Start experiment: 40W + 5W LED lights switched on to prepare the hotbox.
2. Temperature raised too fast, lights switched off.
3. Lights switched on again to reach the optimal temperature between 24°C and 26°C.
4. Switch off the light because of fire safety during the night.
5. Switch on the 40W + 5W lights at the begin of the day to rapidly heat up the hotbox.
6. The 40W light in the aluminium foil is replaced by another 5W light, because the temperature increases too fast.
7. Switch off the 5W + 5W lights.
8. The temperature during the night is increased, meaning that the thermal mass within the hotbox is working even better the longer it is present in the hotbox. The lights were both switched on at 08:30h.
9. Switch off the lights.
10. Switch on the lights.
11. This day, one of the two 5W lights were forgotten to turn off at night, which was beneficial maintaining a warmer, optimal environment for the mycelium sample during the night.
12. Switch on one 5W light.
13. Switch off the lights, sample is taken home for the baking process.

4.1.5 Conclusion

It can be concluded that after this experiment there is no visible evidence that the precise temperature between 24°C and 26°C is a significant factor for mycelium growth. However, these temperatures will still be tried to pursued in subsequent experiments, as the literature suggests that they represent the optimal temperature range for growth. Additionally, the temperatures at the home were relatively consistent with the required temperatures. However, during the winter months, when temperatures naturally decrease, this will no longer be the case. Furthermore, it is inconvenient that the temperature and humidity are not recorded at all times of the day, as is the case with the device in the hotbox provided by Martin Tenpierik. Therefore, the next experiments were held in the hotbox at the TU Delft to ensure an appropriate environment for mycelium growth.



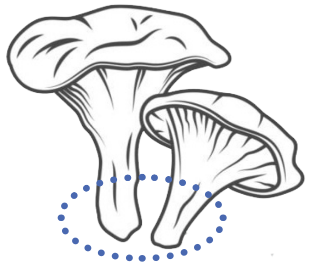
4.2
Mycelium growth with *Pleurotus Ostreatus*

4.2 Experiment 2 | Mycelium growth with *Pleurotus ostreatus* (Grey)

The Pleurotus ostreatus species was the most frequently referenced within the literature review, and thus was selected for initial testing. Given the diverse methods employed in the existing literature, the objective of this experiment is to ascertain the most optimal method for cultivating this species on a defined substrate. The substrate used in this experiment is sterilised cardboard, based on literature where the Stem butt method and the whole mushroom strip method are applied.

4.2.1 Methods

Method	Substrate	Part of *Pleurotus ostreatus*
1	Cardboard	Stem butt
2	Cardboard	Whole mushroom strips
3	Cardboard	Grain spawn

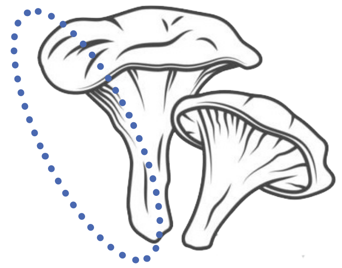


1. Stem Butt Method

The bottom of the Stem of an Oyster Mushroom still has a lot of life force in it, so it will continue to grow if it is placed into the right conditions (simple technique for do it yourself at home cultivation).

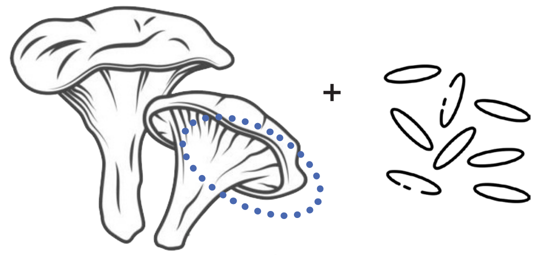
It is less reliable for using grain spawn, because it hasn't such strong growth and less strong yield (because cardboard has not too much nutrients as grain). (GroCycle, 2019)

2. Using the whole Oyster Mushroom



a. Tear up the mushroom into small stripes;
b. Put them in between the cardboard with enough space for the mushrooms to breathe.
c. Place the mould in a warm spot 16°C - 18°C.
d. After two weeks the mycelium has taken over the cardboard.
e. Using gloves: Add material (fungi threads + substrate) to sterile tray, together with the flour. (Field & Forest Products Mushrooms, 2022)

3. Oyster Mushroom Grain Spawn



The grain spawn used for this experiment was originally intended to grow your own grey oyster mushrooms.

a. Make the grow box from a waterproof container;
b. Collect used coffee grounds and let it cool;
c. Inoculate: Mix the mycelium grain spawn with the coffee grounds;
d. Put the container in a warm, dark place.
(Fryslân Fungies, 2024)

4.2.2 Day 1 | Preparations

1. Sterilise everything

At first everything being used is disinfected.
The cardboard will be soaked in boiling water until there are no air bubbles anymore. Afterwards it will be cooled and dried until it stopt dripping. all the surfaces and tools are sterilised with ethanol.

2. Place it into the moulds

The wet cardboard should be squeezed and a layer should be placed into each of the three moulds.

- Stem Butt Method: Cut off the lower part of the mushroom (the stem butt) and add to mould 1;
- Whole Mushroom Method: Tear up the mushroom into small strips and add to mould 2;
- Grain Spawn Method: Spread the grain spawn over the cardboard layer, spawn rate of 10% - 20%;

These steps are repeated until the mould is filled. A final cover layer of squeezed cardboard is put on top as final layer. Then the mould is coveren with plastic foil and holes are poked into this foil to allow oxygen to each the material while growing.

3. Store it on a dark and warm place

The samples are stored in a drawer for two days, because the mycelium grows the first few days best in the dark (Appendix 8.1.4, row 4.3). The temperature within the drawer was at daytime between 25,5°C and 27,5 °C and in the night between 23,5°C and 25°C.

4.2.3 Growing process

On day 3, the samples were moved to the hotbox at TU Delft, as the temperature at home was expected to drop due to the weather forecast and the samples need a humid environment to grow better. The thermal mass from the PCM material from the last experiment was still present in the hotbox. The temperature inside the hotbox during this experiment is shown in Figure 28 on page 44.

1. Stem butt method

A small amount of mycelial growth is visible on day 3, but by the eighth day, this method exhibited the earliest indications of mould development among the three methods.. Following the tenth day, the development of external mould led to the decision to cancel the experiment utilising the stem butt method.

2. Whole mushroom strip method

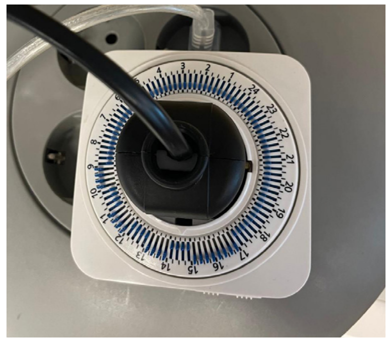
In addition to my initial hypothesis, this method showed a similar rate of mycelial growth to the other two methods. By day 3, the first development was evident. However, by day 12, mould formation had also occurred, resulting in the cancellation of this experiment.

3. Grain spawn method

Based on the available literature, this method was expected to be the most effective. This proved to be the case, with the mycelium growth occurring rapidly, although not more so than in the other two methods. However, mould formation occurred on the 12th day, which meant that this last method was also not fully successful in this experiment.

Time-controlled device added

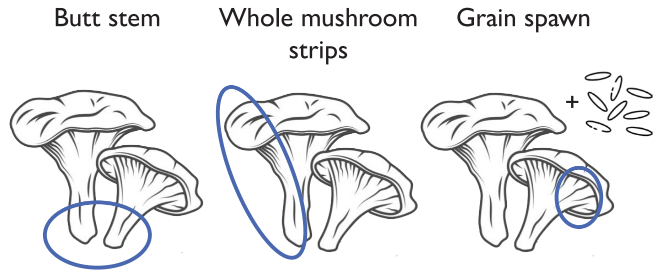
During the initial nine-day period, the internal temperature of the hotbox remained consistent at approximately 25°C without the need of any additional heat sources to maintain the optimal conditions for mycelial growth. On the 10th day, however, this was no longer the case and the temperature was lowered due to the onset of colder weather conditions. Consequently, the 12W LED light was reinstalled, and a time-controlled device was employed to automate its hourly activation and deactivation cycles. This was set to switch on and off at 9:00 a.m. and 5:00 p.m., respectively, in line with fire safety regulations. The device was programmed to switch on and off at hourly intervals, as otherwise the temperature within the hotbox would increase significantly when the LED lamp was in operation for the entire day, from 9:00 to 17:00.

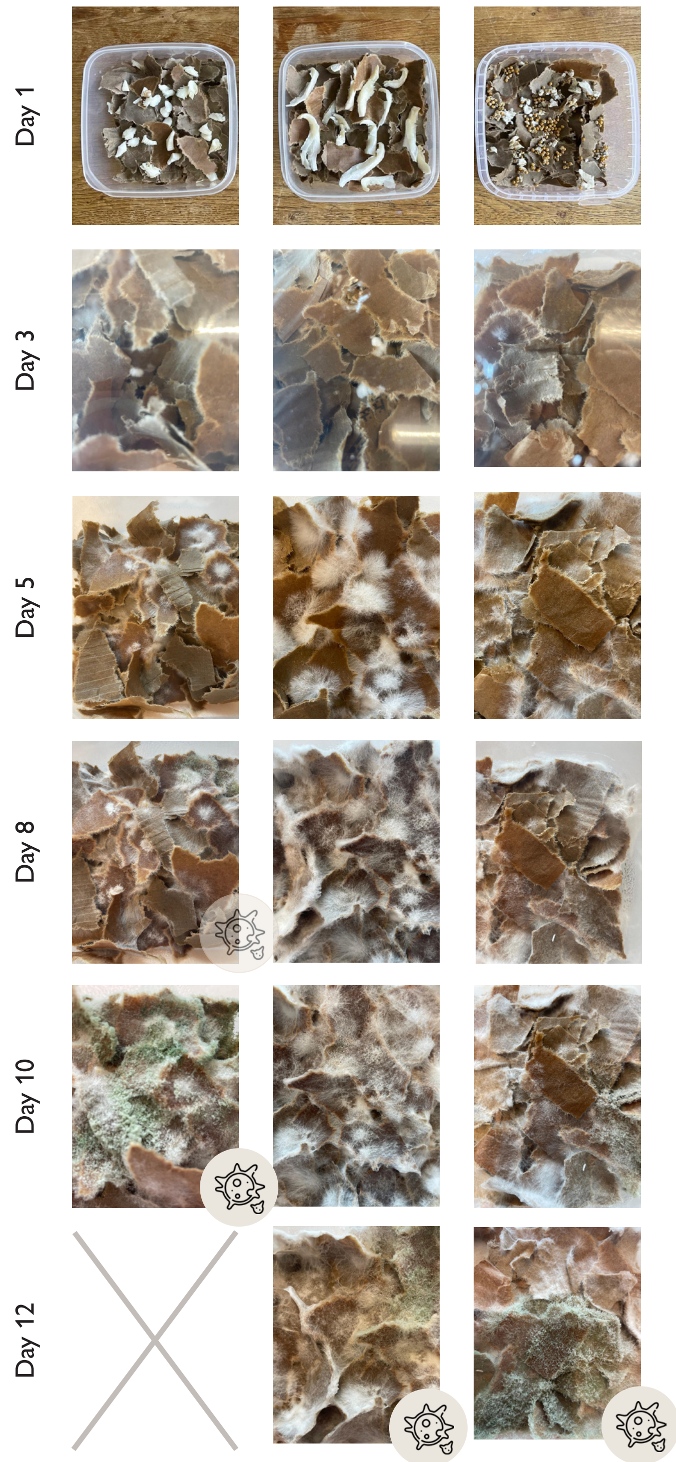


Time-controlled device

Growing process on cardboard

Part of the mushroom





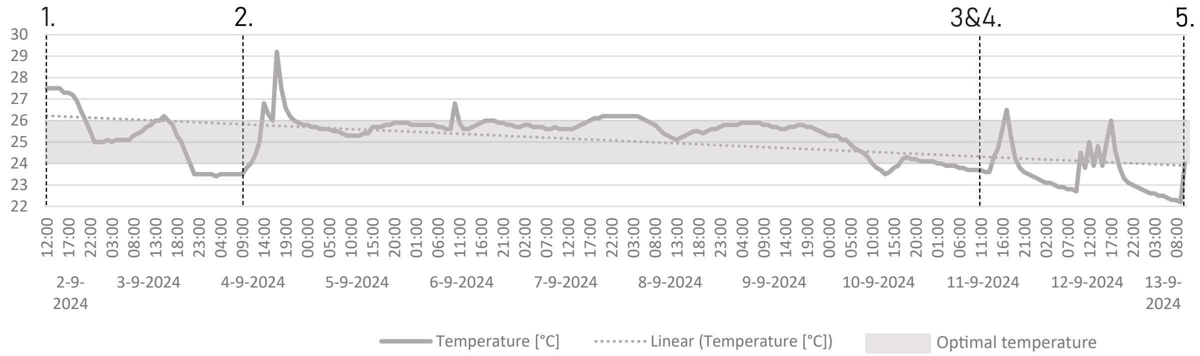


Figure 28. Temperature diagram during experiment 2 (Based on information provided from the app 'AranetHome', own work)

4.2.4 Temperature diagram

1. Growth in dark drawer at home.
2. Samples moved to hotbox TU Delft.
3. Time-controlled device for LED lights added.
4. Stem Butt Method experiment discontinued due to mould development.
5. Other two methods also discontinued due to mould development

4.2.5 Conclusion

The three methods showed that mycelium is able to be cultivated on the selected substrate, namely sterilised cardboard, with all three of the methods. The Stem butt method was the first to demonstrate the development of mould, but it remains worthwhile to attempt this method with other substrates, as it is possible that the presence of an unsterilised element during the preparation phase was the cause of the accelerated mould growth.

The reason for the occurrence of mould in this experiment remains unclear. The fact that this fungal development occurred earlier in the stem-butt method is also uncertain. It is possible that external bacteria may have gained access to one of the tools or surfaces used. Therefore, in future experiments, special attention will be paid to the sterility of the environment and the tools.

	Date	Purpose	Substrate	Fungi species	Sterilized?	Humidity level [%]	Light influence	Duration	Growth discription	Further testing?	Pressed?	Comments
1	17.06.24	Growth process testing with regulated conditions	Hemp fibres	Unknown	Yes	42 - 51	Artificial light	5 days		No	Hand-pressed before growing process	
	17.06.24	Growth process testing without regulated conditions	Hemp fibres	Unknown	Yes	?	Natural light	5 days		No	Hand-pressed before growing process	
2	02.09.24	Mushroom testing	Cardboard	Pleurotus Ostreatus (Grey): **Stem Butt**	Yes	53 - 61	Natural light & artificial light	10 days	Fast, mould development after 7 days	No, not flexible enough	No	
	02.09.24	Mushroom testing	Cardboard	Pleurotus Ostreatus (Grey): **Whole Mushroom Strips**	Yes	53 - 61	Natural light & artificial light	12 days	Fast, mould development after 12 days	No, not flexible enough	No	
	02.09.24	Mushroom testing	Cardboard	Pleurotus Ostreatus (Grey): **Grain Spawn**	Yes	53 - 61	Natural light & artificial light	12 days	Fast, mould development after 12 days	No, not flexible enough	No	
3	02.09.24	Substrate testing	Corn granules	Pleurotus Ostreatus (Grey): **Grain Spawn**	No	53 - 61	Natural light & artificial light	8 days untill cancelled	No visible growth	No	No	No option to sterilise this substrate & no waste stream, so cancelled
	02.09.24	Substrate testing	Coffee grains	Pleurotus Ostreatus (Grey): **Stem Butt**	Yes	53 - 61	Natural light & artificial light		Fast	No	No	
	18.09.24	Substrate testing	Coffee grains	Pleurotus Ostreatus (Grey): **Whole Mushroom Strips**	Yes	53 - 61	Natural light & artificial light		Fast	No	No	
	18.09.24	Substrate testing	Coffee grains	Pleurotus Ostreatus (Grey): **Grain Spawn**	Yes	53 - 61	Natural light & artificial light		Fast	Yes	No	
	02.09.24	Substrate testing	Cotton pads	Pleurotus Ostreatus (Grey): **Grain Spawn**	No	53 - 61	Natural light & artificial light	8 days	No visible growth	No	No	Experiment cancelled after 8 days
	02.09.24	Substrate testing	Cotton cloth	Pleurotus Ostreatus (Grey): **Grain Spawn**	No	53 - 61	Natural light & artificial light	8 days	No visible growth	No	No	Experiment cancelled after 8 days
	11.09.24	Substrate testing	Cotton cloth	Pleurotus Ostreatus (Grey): **Grain Spawn**	Yes		Natural light & artificial light	5 days	Fast growing rate, after 5 days growth stopped	Yes	No	
	02.09.24	Substrate testing	Jute	Pleurotus Ostreatus (Grey): **Grain Spawn**	No	53 - 61	Natural light & artificial light	8 days	No visible growth	No	No	Experiment cancelled after 8 days
	11.09.24	Substrate testing	Jute	Pleurotus Ostreatus (Grey): **Grain Spawn**	Yes		Natural light & artificial light	5 days	Fast growing rate, after 5 days growth stopped	Yes	No	
	11.09.24	Substrate testing	Oak Sawdust	Pleurotus Ostreatus (Grey): **Stem Butt**	Yes		Natural light & artificial light	7 days until cancelled	Fast development of mould	No	Hand-pressed before growing process	Mould development after 9 days, experiment again started at 18.09.24
	11.09.24	Substrate testing	Oak Sawdust	Pleurotus Ostreatus (Grey): **Whole Mushroom Strips**	Yes		Natural light & artificial light	7 days until cancelled	Fast development of mould	No	Hand-pressed before growing process	Mould development after 9 days, experiment again started at 18.09.24
	11.09.24	Substrate testing	Oak Sawdust	Pleurotus Ostereatus (Grey): **Grain Spawn**	Yes		Natural light & artificial light	26 days until cancelled	Very slow growing rate	No	Hand-pressed before growing process	
	27.09.24	Substrate testing	Oak Sawdust	Pleurotus Ostreatus (Grey): **Grain Spawn**	Yes		Artificial light	15 days untill cancelled	Only a bit development of mould	No	No	
	07.10.24	Substrate testing	Oak Sawdust: soaked in boiling water | pressed	Pleurotus Ostreatus (Grey): **Grain Spawn**	Yes		Artificial light				Hand-pressed before growing process	Mould developement after 10 days
	07.10.24	Substrate testing	Oak Sawdust: soaked in boiling water | not pressed	Pleurotus Ostreatus (Grey): **Grain Spawn**	Yes		Artificial light				No	
	07.10.24	Substrate testing	Oak Sawdust: soaked in boiling water | not pressed + flour	Pleurotus Ostreatus (Grey): **Grain Spawn**	Yes		Artificial light				No	
	18.09.24	Substrate testing	Hemp fibers	Pleurotus Ostreatus (Grey): **Stem Butt**	Yes	53 - 61	Natural light & artificial light	12 days untill cancelled	Mould development	No	Hand-pressed before growing process	
	18.09.24	Substrate testing	Hemp fibers	Pleurotus Ostreatus (Grey): **Whole Mushroom Strips**	Yes	53 - 61	Natural light & artificial light		Slow	No	Hand-pressed before growing process	
	18.09.24	Substrate testing	Hemp fibers	Pleurotus Ostreatus (Grey): **Grain Spawn**	Yes	53 - 61	Natural light & artificial light			Yes	Hand-pressed before growing process	
	27.09.24	Substrate testing	Hemp fiber mat	Pleurotus Ostreatus (Grey): **Grain Spawn**	Yes		Artificial light			Yes	No	
	27.09.24	Substrate testing	Flax fiber mat	Pleurotus Ostreatus (Grey): **Grain Spawn**	Yes		Artificial light			Yes	No	

Figure 29. Framework experiment 1, 2 and 3 (with *Pleurotus ostreatus*), own work

4.3
Substrates with *Pleurotus ostreatus*

4.3 Experiment 3 | Substrates with *Pleurotus ostreatus* (Oyster mushroom)

"What are the most suitable substrates for optimizing the growth and performance of mycelium-based composites?"

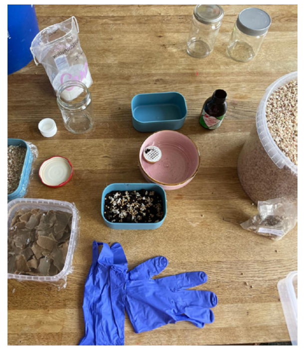
This experiment was carried out partly at home (the first two days of each substrate experiment) and mostly in the hotbox at the TU Delft, to test which substrate grows best on the *Pleurotus ostreatus* species (Oyster mushroom) used in the three methods explained in the previous chapter.

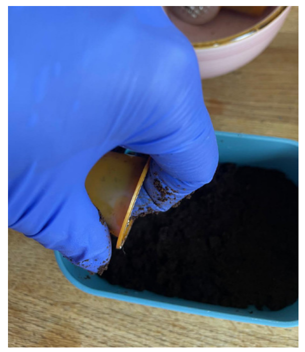
In the following pages, all figures with three images next to each other are in the order from left to right: Stem Butt method, whole mushroom strips, grain spawn.

4.3.1 Method

This experiment is not in chronological order, but the order is determined by the type of material. First the granular materials, then the loose fibers, and finally the woven materials.

Not all experiments were started at the same time, as new literature and discussions with experts added new relevant experimental possibilities. After a period of observation, it became evident that the grain spawn method was the most effective in terms of mycelial species with minimal mould development, a rapid growth rate and a more homogeneous appearance. Consequently, it was no longer necessary to apply all three methods to all substrates, which were still to be tested. Therefore, not all three methods were applied to all substrates.





4.3.2 Granular materials as substrate

1. Coffee grains

The coffee grains utilized in this experiment were sourced from the cups of a Nespresso machine at home. They were then opened and the grains extracted and positioned within the mould.

In the first three days of the experiment, there was already a slight development of mycelial spots on the coffee grains using all three methods. Thereafter, the growth rate demonstrated a notable rapidity, and by day 15, the mycelium had fully colonised the grains without any external visible signs of mould development.

In this particular application, the use of coffee grains is not a particularly useful approach, as the available literature indicates that the majority of coffee-ground-based composites lack the requisite strength. In comparison with sawdust, its compressive strength is significantly lower (Alemu et al., 2022). In addition, it is widely acknowledged that a significant proportion of the strength of mycelium-based composites is derived from the substrate.

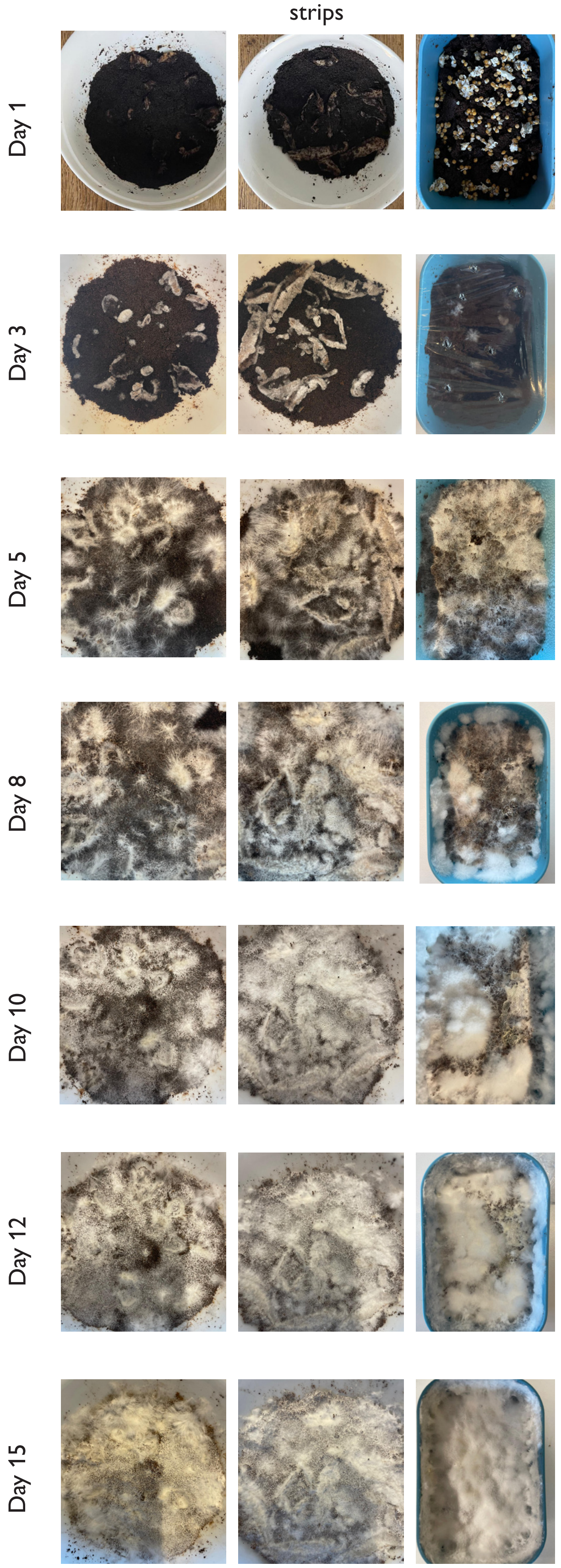
Three criteria for using a substrate:

1. Enough cellulose for the fungi to feed on; ✔
2. Mechanical strength; ✘
3. Formability. ✔

Growing process on coffee grains

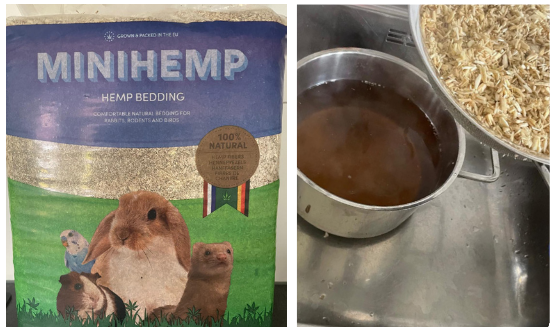
(granular material)

Butt stem | Whole mushroom strips | Grain spawn



2. Hemp fiber particles

The hemp utilized in this experiment was obtained from a pet shop and is naturally suited for use as bedding material for rabbits, rodents, and birds. It was initially sterilized through boiling, then drained and placed into the molds. During the sterilization process, the hemp released a distinctive woody aroma, and the water it was boiled in took on a brown hue.



The stem butt method resulted in a slower growth rate than the other two methods, and external mould development was observed after 10 days. Following this, the method was discontinued within the substrate. The other two methods were successful, as illustrated in the figure on the right.

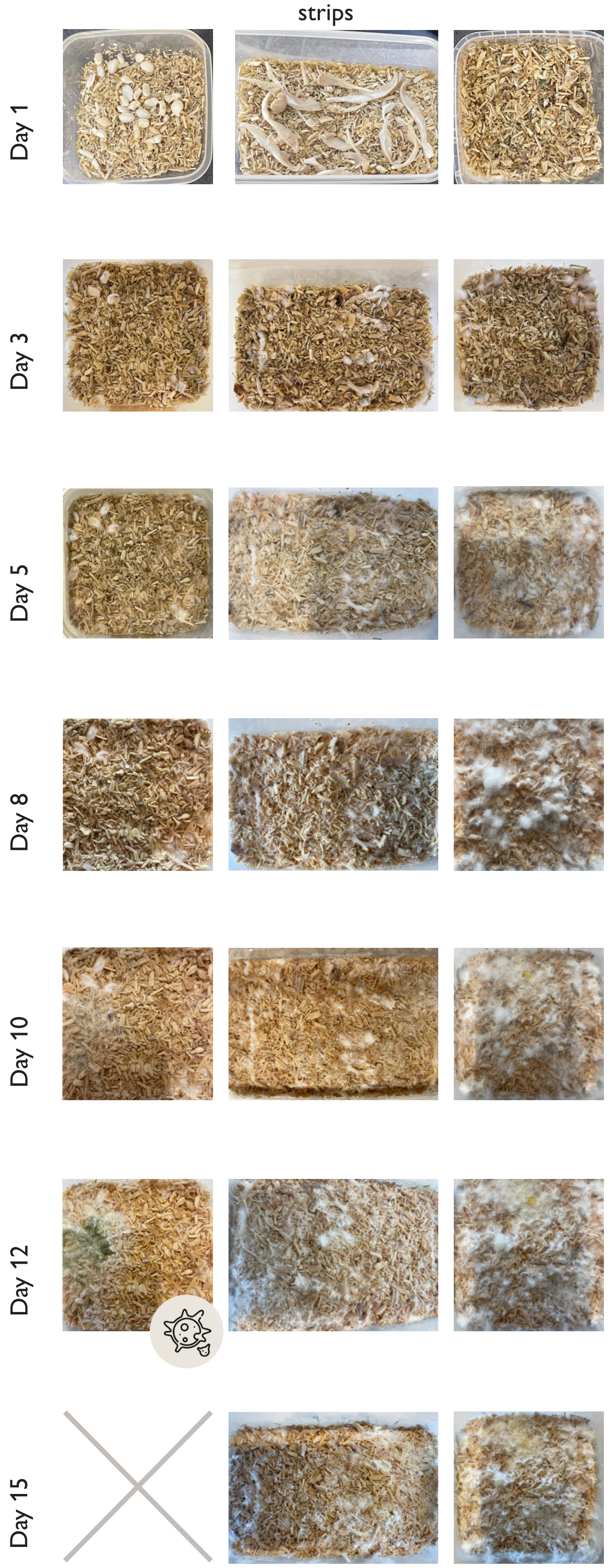
Three criteria for using a substrate:

1. Enough cellulose for the fungi to feed on; ✔
2. Mechanical strength; ✔
3. Formability. ✔

Growing process on hemp fiber particles

(granular material)

Butt stem | Whole mushroom strips | Grain spawn



3. Oak sawdust | Dry | Pressed

In consideration of the fact that the substrate had already undergone sterilisation by the manufacturer before delivery, it was assumed that boiling water would not be required for the purpose of sterilisation.The substrate was then poured dry into the mould and mixed with the mushroom parts. At day 5, there was a slight development of mycelium visible at the whole mushroom method, but a few days later, this changed into external mould development. Additionally, the stem butt method showed visible external mould development at day 10, indicating that these two experiments were unsuccessful and should be discontinued.

The grain spawn method did not show any notable developments until day 12, when a small amount of mycelium growth was observed. However, following 15 days of minimal mycelial development, this experiment was also terminated.

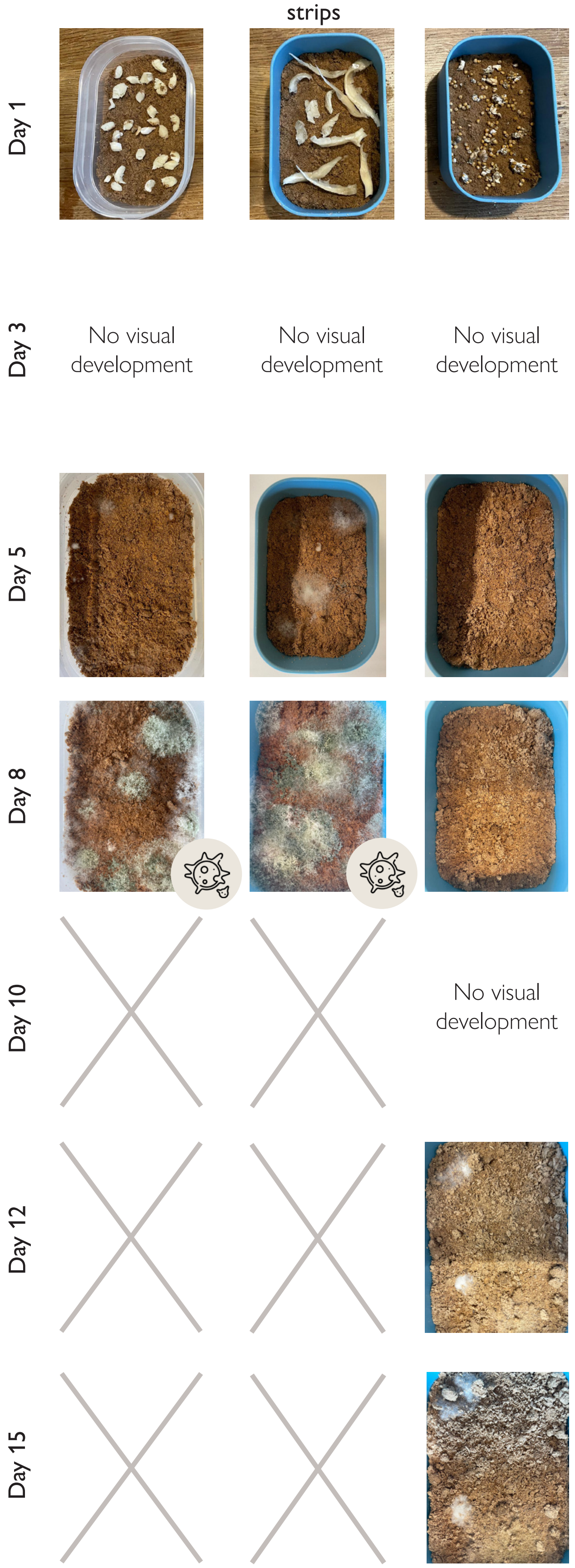
Three criteria for using a substrate:

1. Enough cellulose for the fungi to feed on; ?
2. Mechanical strength; ✓
3. Formability. ✓

Growing process on sawdust pressed | dry (not soaked in boiling water)

(loose material)

Butt stem | Whole mushroom strips | Grain spawn



4. Oak sawdust | Soaked in boiling water

In analysing the results of the experiment utilising dry, pressed (i.e., not soaked in boiling water) sawdust, it was determined that the grain spawn method should be pursued further. This approach did not result in the formation of external mould, yet no mycelium was observed. The reason for this could be that the mycelium requires a higher moisture content to facilitate growth; this will be tested within the current experiment. Additionally, a lack of mycelium development may be attributed to the need for greater space and oxygen for the mycelium to breathe and grow. There is also a possibility that the mycelium requires a preliminary boost in order to grow within this substrate. One potential solution is the use of flour as a kickstarting material, which may facilitate the growth process (Appendix 8.1.5 and 8.1.6). To address this, three methods will be applied within the current experiment:

- Oak sawdust soaked in boiling water, pressed;
- Oak sawdust soaked in boiling water, unpressed;
- Oak sawdust soaked in boiling water, unpressed and with added flour (10% of the total mass).

The figure on the right illustrates the development of the mycelium, which is evident from day 3 onwards. This demonstrates that the addition of humidity to the material is conducive to mycelium growth.

A comparison of the addition of flour (right) and the lack of flour (middle) demonstrates that the added flour plays a role in kickstarting the mycelium, as the sample with added flour shows faster mycelium growth.

A comparison of the samples with and without pressing (left and middle, respectively) reveals that the pressed sample exhibits even more rapid mycelial growth than the non-pressed sample, further highlighting the impact of pressure on this particular aspect of fungal growth. This indicates that the mycelium is capable of growth even in the presence of reduced oxygen levels between the mycelium grains.

The application of all three methods resulted in the formation of an external mould. While this outcome is disappointing, the potential of the substrate remains a topic of further investigation, given the existing literature which suggests it has promising characteristics. In the course of subsequent testing, particular attention will be paid to maintaining a clean environment.

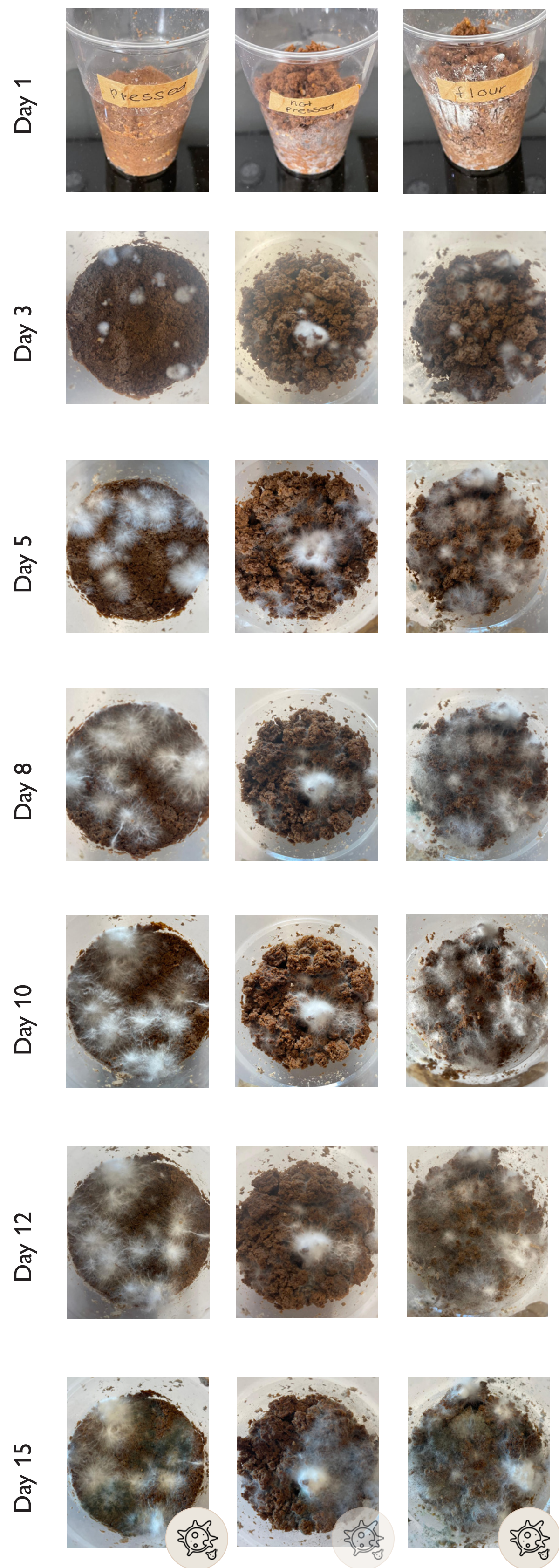
Three criteria for using a substrate:

1. Enough cellulose for the fungi to feed on; ✓
2. Mechanical strength; ✓
3. Formability. ✓

Growing process on sawdust Soaked in boiling water | Grain spawn

(loose material)

Pressed | Not pressed | Not pressed with added flour



4.3.3 Loose fibers

At the beginning of the experiment, it was evident that the grain spawn method was the most appropriate to continue with, as demonstrated by the presence of external mould development in the substrates using the other two methods in the earlier stages of the experiment. Furthermore, this method is more effective in producing a more homogeneous final sample.

1. Hemp fiber mat (left)
In this experiment, a fibreous mat of hemp was utilised. The grain spawn was poured over the layer to test its ability to grow on the material. This was indeed the case, however, the material remained not homogeneous, with the mycelium only developing at the points of placement. This resulted in a final sample with limited strength, as the mycelium had not fully colonised the entire material.

2. Flax fiber mat (right)
A comparable material to the hemp fibre mat is employed in this experiment, specifically a flax fibre mat with visual characteristics that are for the most part identical. The grain spawn is also poured over one layer of this material to ascertain its capacity for growth. This also proved to be the case with this material, resulting in a similar growth rate and visual appearance. However, the same issue was observed: the material remained not homogeneous. with the mycelium only developing at the points of placement. So, this also resulted in a final sample with poor strength.

Three criteria for using a substrate:	
1. Enough cellulose for the fungi to feed on;	✓
2. Mechanical strength;	✗
3. Formability.	✓

Growing process grain spawn on fiberous mats
Hemp & Flax
(fibers)

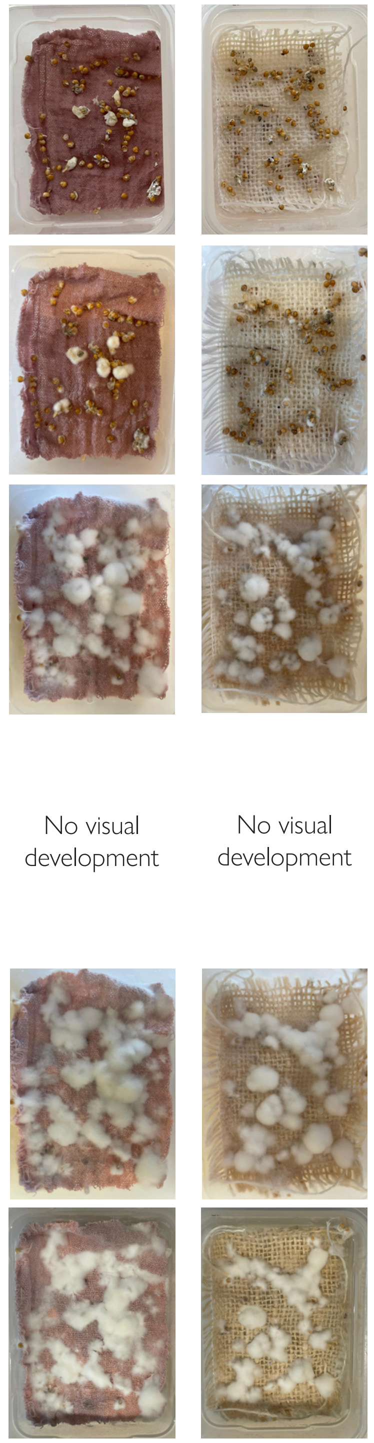
4.3.4 Woven materials

1. Cotton
In this experiment, a woven fabric sheet of cotton was utilised. The grain spawn was poured over the layer to test its ability to grow on the material. This was indeed the case, however, the material remained not homogeneous, with the mycelium only developing at the points of placement. This resulted in a final sample with the same tensile strength as a woven cotton sheet without mycelium. This indicates that further testing is required to assess the capacity to connect different layers of this material.

2. Jute
In this experiment, a comparable material to the woven cotton sheet is employed, specifically a woven jute sheet with different visual characteristics. The distance between the two fibres of the jute is greater, thereby allowing the mycelium more space to grow through the material. The grain spawn is also poured over one layer of this material to ascertain its capacity for growth. This also proved to be the case with this material, resulting in a similar growth rate and visual appearance. However, the same problem was observed: the material remained not homogeneous. with the mycelium only developing at the points of placement. So, this also resulted in a final sample with the same tensile strength and characteristics as the substrate jute itself. This also suggests the necessity for further testing in order to evaluate the capacity to create connections between the various layers of this material.

Three criteria for using a substrate:	
1. Enough cellulose for the fungi to feed on;	✓
2. Mechanical strength; *Tensile strength*	✓
3. Formability.	✓

Growing process grain spawn on woven materials
Cotton & Jute
(woven material)



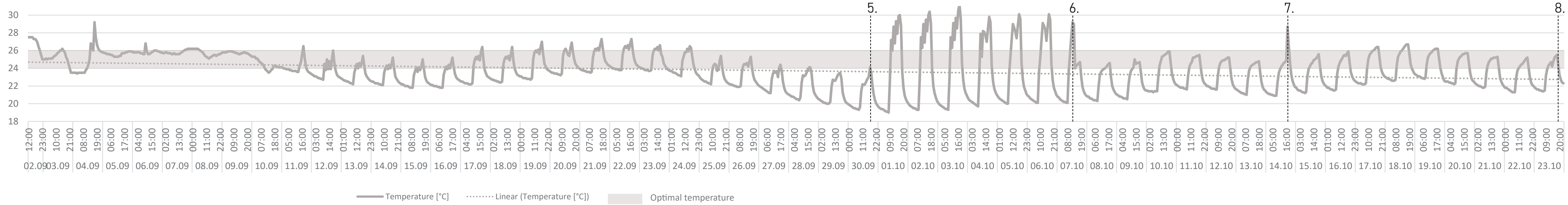


Figure 30. Temperature diagram during experiment 3 (Based on information provided from the app 'AranetHome', own work)

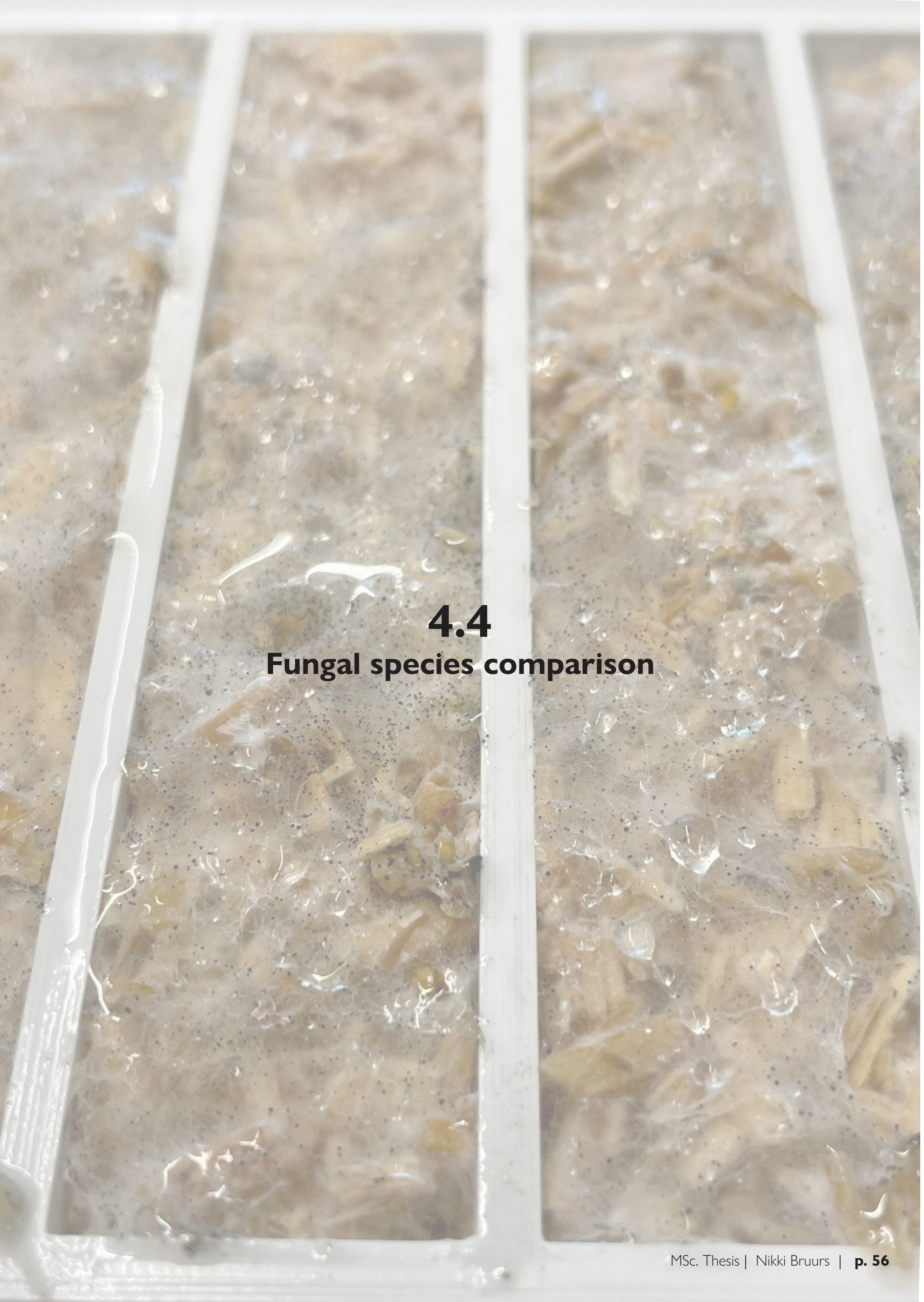
4.3.5 Temperature diagram

1. Start coffee grains – Grain Spawn experiment together with cardboard mushroom part experiment;
2. Start cotton cloth & jute – Grain spawn experiment, start Oak sawdust experiment and time-controlled device for LED lights added;
3. Start again Oak sawdust – Butt Stem & Whole mushroom experiment, start coffee grains – Butt Stem & Whole Mushroom experiment and start Hemp fibres experiment;
4. Start Oak Sawdust not pressed experiment, Start hemp fibres mat and flax fibres mat experiment;
5. Switch from 12W to 23W because the weather outside is getting colder and colder, and so is the temperature inside the hotbox. Also the heating system at the faculty does not work anymore.
6. Switch back from 23W to 12W because the temperature raised too fast. Also added a tray filled with water, to improve the humidity level.
   Start experiment oak sawdust soaked in boiling water (pressed, unpressed and with added flour).
7. 60W LED light for 10 minutes added to quickly increase the temperature.
8. End of experiment, last sample (soaked oak sawdust unpressed) had mould development.

4.3.6 Conclusion

In conclusion, the experiment focused on the use of grain spawn with cotton, jute, hemp fibre mat, and flax fibre mat substrates, as it became evident in the later phase of the study that alternative methods led to increased mould development. Based on the outcomes observed in both this experiment and the supporting literature, the substrates hemp fibre particles, oak sawdust (soaked in boiling water), woven cotton, and woven jute were selected for further testing due to their favourable results, including minimal mould growth and relatively rapid mycelial development.

However, while cotton and jute demonstrated mycelial growth at the points where the grain spawn was placed, this development was not uniform, indicating a need for further research. Further testing will be done to explore the potential of creating a more homogeneous material by layering fabric sheets with mycelium in between. Despite some contamination in the oak sawdust soaked in boiling water, its favourable properties noted in the literature make it a suitable material for further investigation. These findings suggest that continued exploration of these substrates is essential for optimising mycelial growth and enhancing material properties.



4.4
Fungal species comparison

4.4 Fungal species comparison
Pleurotus ostreatus vs. Ganoderma lucidum

"What are the most suitable fungal species for optimizing growth and performance of mycelium-based composites?"

4.4.1 Preparations

In the MyxSail reference on page 23, the additional mycelium was in the form of grain inoculated with spores of the oyster mushroom (*Pleurotus ostreatus*) and the grains were incorporated between layers. This technique is also employed in the fabrication of samples consisting of jute and cotton blended with the *Pleurotus ostreatus* species.

In the framework of this experiment, a new mycelium species is introduced for the purpose of comparing the *Pleurotus ostreatus* species with *Ganoderma lucidum*. This species has been selected on the basis of recommendations from numerous experts, who have advised a more in-depth investigation of *Ganoderma lucidum*. In the case of the new introduced mycelium species, Hedelcomposite is used in place of grain spawn. Hedelcomposite is composed of sterilised sawdust residuals and inoculated with mycelium. It is ready for immediate use. The objective is to cultivate biodegradable mycelium objects with Hedelcomposite in a period of approximately one week (HedelComposite - 10KG ~20L | Kineco Mycelium, n.d.). Given that the Hedelcomposite contains smaller and lighter particles than the grain spawn, this sawdust-like material is blended with the material in a bowl. The sterilised material adheres to the surface due to its boiling water sterilisation and residual moisture content.

To ensure the accuracy of the weight and ratio, the sterilised hemp, sawdust, cotton or jute will be placed in the bowl and weighed initially. Subsequently, the mycelium will be added (representing 20% of the total weight), and its weight will be recorded. Following this, the flour will be added (representing 10% of the combined weight of the substrate and mycelium). The mixture will then be thoroughly mixed, and it will be placed in the moulds. In the case of the cotton and jute, these will be placed in the moulds layer by layer.

Pleurotus ostreatus
Grain spawn

Ganoderma lucidum
Hedelcomposite

It should be noted that the scale of the two images above is not identical. The grain spawn is contained within a 1 kg bag, whereas the hedelcomposite is present in a 10 kg (20 L) bag.

Sterilise substrate and weigh

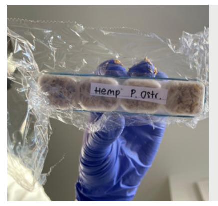
+

Add 20% of total weight **grain spawn** or **hedelcomposite**

+

Add 10% of total weight **flour**

Mix very well & Put in mould



Label & Add plastic foil with holes for oxygen

↓

8x ***Pleurotus Ostreatus***
Hemp fiber particles
20 x 22 x 20 mm

8x ***Ganoderma Lucidum***
Hemp fiber particles
20 x 22 x 20 mm

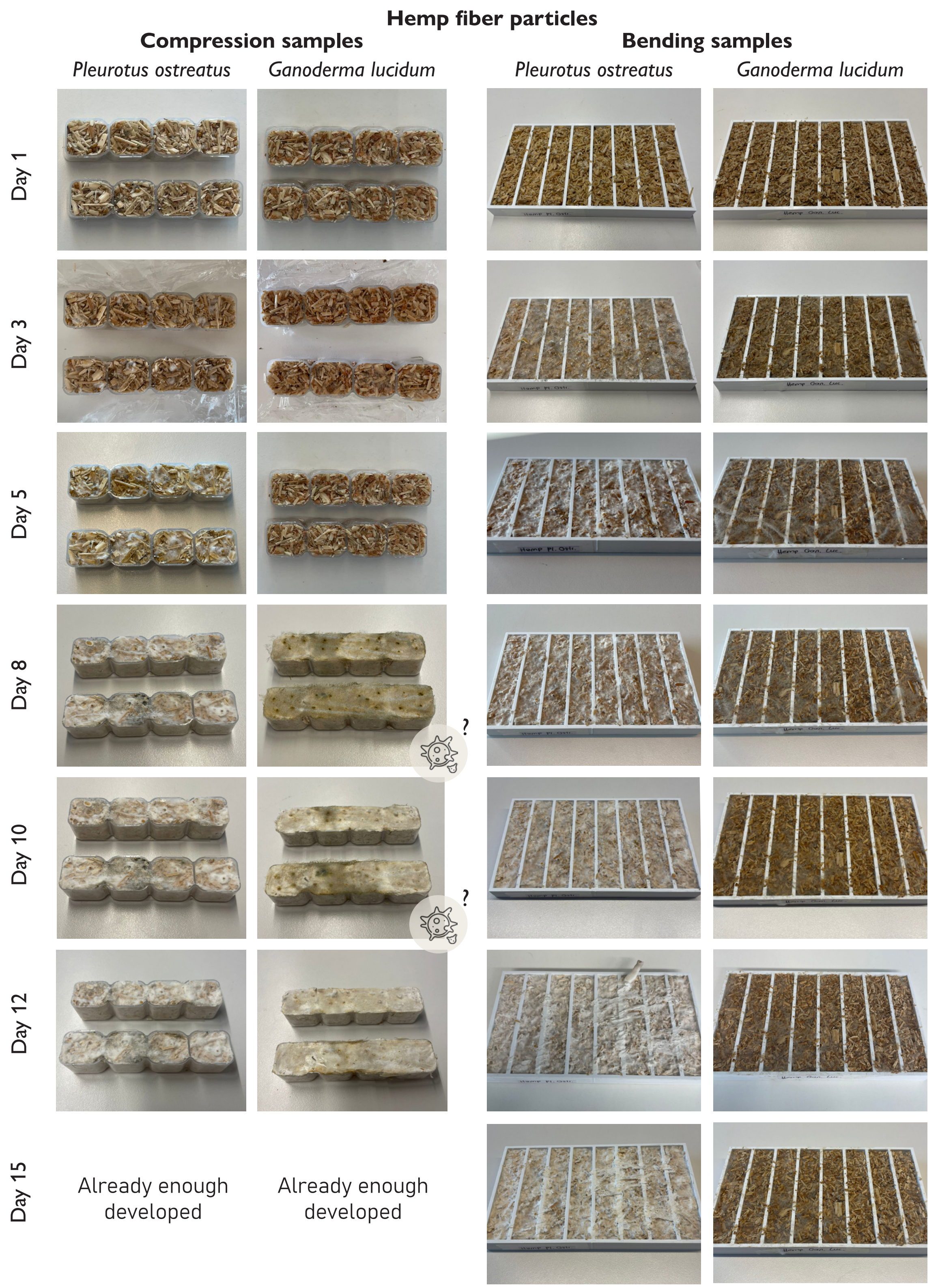
4.4.2 Hemp fiber particles

1. Compression samples

The initial mycelium development was observed in samples of the *Pleurotus ostreatus* species, leading to the hypothesis that these samples would reach full growth at an earlier stage. However, after the initial five-day period, the *Ganoderma lucidum* species demonstrated comparable growth rates. Unfortunately, external mould development was observed in these samples. However, this was rapidly resolved, with the external mould no longer evident by the end of the observation period. This outcome may be attributed to the mycelium fungi's greater resilience against external moulds, which has also been documented in the literature.

2. Bending samples

The bending samples exhibited unusual behaviour. The *Pleurotus ostreatus* samples demonstrated a growth rate comparable to that of the compression samples. However, the *Ganoderma species* presented a markedly different pattern of growth. At day 5, a grey fluffy haze was observed over the hemp, yet no further development of the mycelium threads was evident. The reason for this remains unclear. Potential explanations for this outcome include an error in the mixing process or the formation of external moulds that are not visible. However, the combination of hemp and *Ganoderma lucidum* will be tested further, given that it was effective with the compression samples.



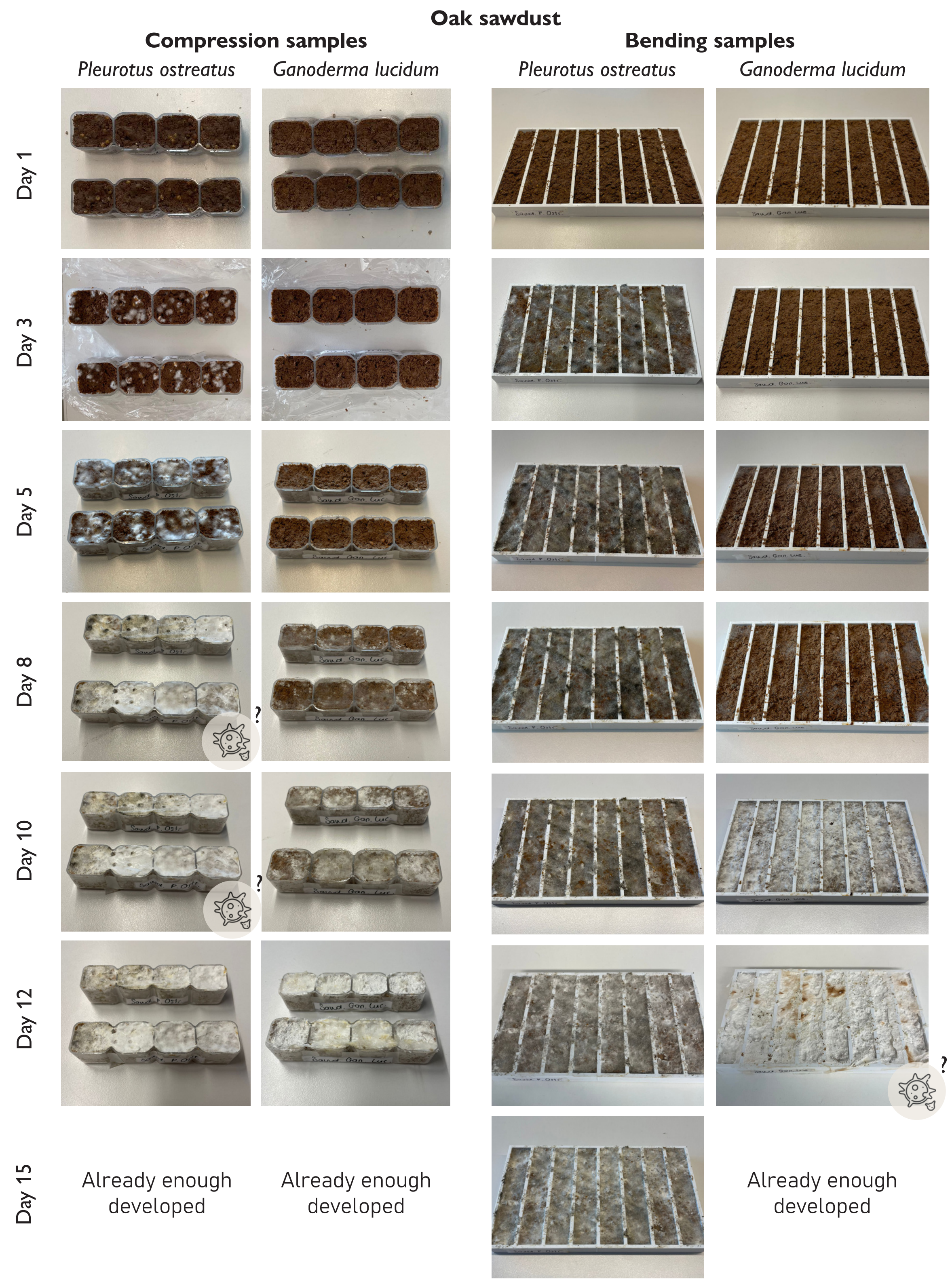
4.4.3 Oak sawdust

1. Compression samples

The *Pleurotus ostreatus* once again demonstrates the fastest mycelium development since day 3. However, from day 8, some white areas emerge in the *Ganoderma lucidum* samples, and from day 10, the growth process accelerates significantly. In the case of the *Pleurotus ostr.* samples, there appears to be evidence of external mould development between days 8 and 10. However, by day 12, this has resolved itself, and the external mould has disappeared.

2. Bending samples

It is evident that the *Pleurotus ostr.* species is demonstrating accelerated growth, whereas the *Ganoderma luc.* species exhibits a temporally delayed growth rate with a relatively rapid final growth phase. Ultimately, the *Ganoderma luc.* species has developed at a faster rate, although its initial growth was slower. However, it is noteworthy that some unusual orange-like spots have emerged on the surface of these samples, which may have an impact on the overall quality and characteristics of the samples.



4.4.4 Woven cotton

1. Compression samples

In comparison to the hemp and sawdust samples, the cotton samples demonstrate a less homogeneous growth pattern. From day five of the experiment, it was observed that a small quantity of mycelium was present within the *Pleurotus. ostr.* samples. Additionally, external mould was noted at specific locations within the samples. It appears that the mycelium is not truly developing through the layers, but rather on the exterior. A similar process was observed in the *Ganoderma. luc.* samples. A grey-ish layer of mycelium threads became visible from day 5, but its development was minimal. From day 12, external mould was also visible.

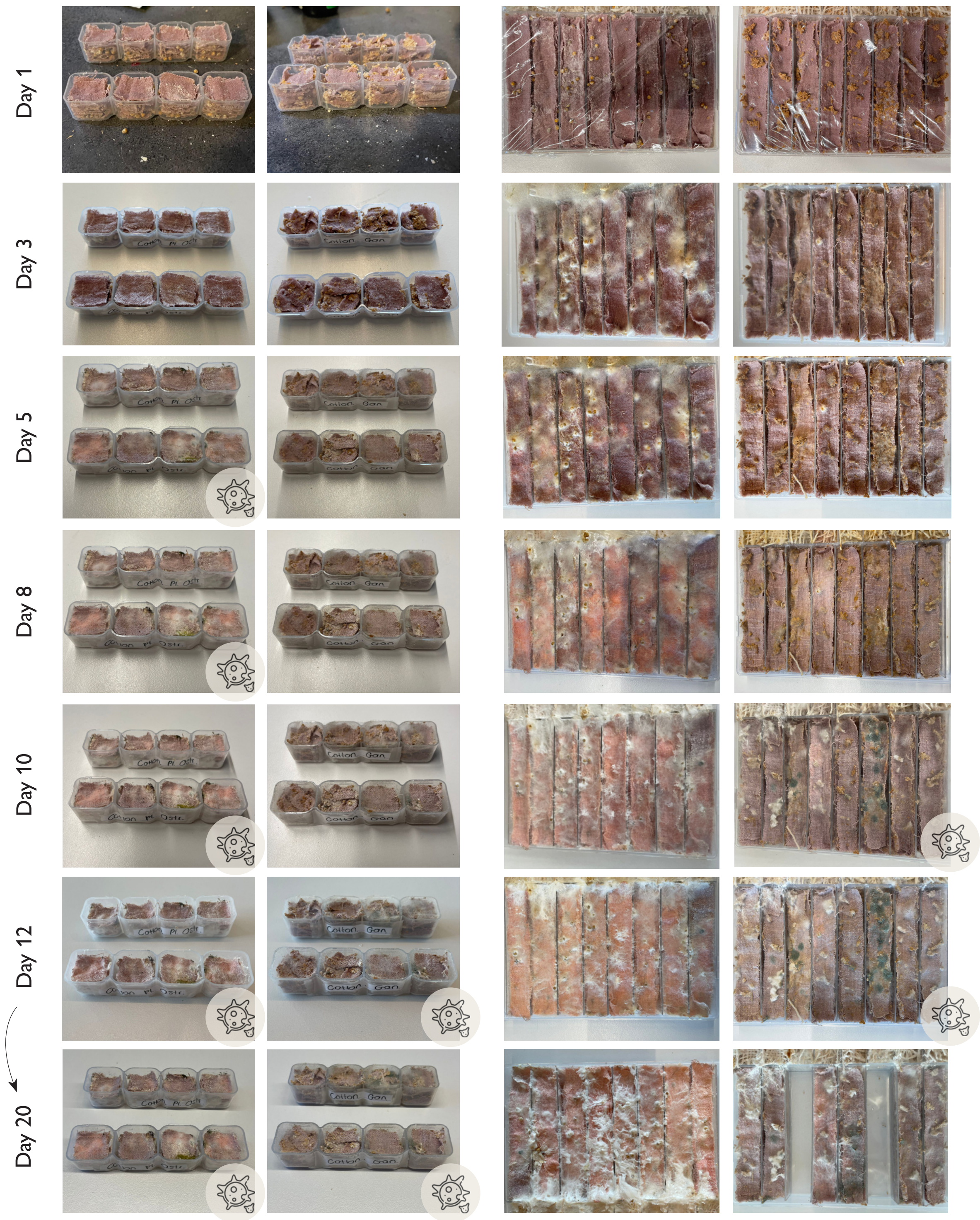
2. Bending samples

Additionally, the mycelial development within the bending samples was also observed to be limited to the outer layer, with minimal progress observed through the layers. It is possible that the pores of this material may be insufficient in size to permit the growth of the mycelium. In the case of the *Pl. ostr.* samples, mycelial development was first observed on day 3, but from that point onwards, there was minimal further development and no evidence of homogeneity. The *Gan. luc.* samples exhibited mycelium development on day 10, with the appearance of greyish threads and external mould development. It can be concluded that the growth rate with both species is minimal with this substrate. Therefore, it can be hypothesised that the problem lies not with the species, but with the substrate.

Woven cotton

Compression samples | **Bending samples**

Pleurotus ostreatus | *Ganoderma lucidum* | *Pleurotus ostreatus* | *Ganoderma lucidum*



4.4.5 Woven jute

1. Compression samples

The distribution of the mycelium in relation to the substrate was also not optimal with this material. The mycelium exhibited preferential growth on the outer surface of the samples. From day 5, mycelial development was evident in both species, but from day 12, external mould formation was observed in the *Ganoderma lucidum* samples. After 20 days, this phenomenon became more significant. Additionally, for both species, the material did not develop homogeneously across the entire sample, which was likely due to the mycelial threads being unable to fully establish themselves through the layers.

2. Bending samples

In the case of the *Pl. ostr.* samples, the initial mycelium development was observable as early as day 3, with a notable acceleration in development over time. It appears that this species is capable of developing on this substrate; however, the tensile strength of the samples is relatively low, as the mycelium has exhibited limited vertical growth through the layers. In the case of the *Gan. luc.* species, the initial indications of mycelium development became visible at day 10, but following this, there was minimal further development. It is noteworthy that the jute became pink in some areas, which is likely due to the fact that the jute and the cotton were placed in the same mould and the colouring has transferred slightly to the other side.

Woven jute

Compression samples | **Bending samples**

Pleurotus ostreatus | *Ganoderma lucidum* | *Pleurotus ostreatus* | *Ganoderma lucidum*

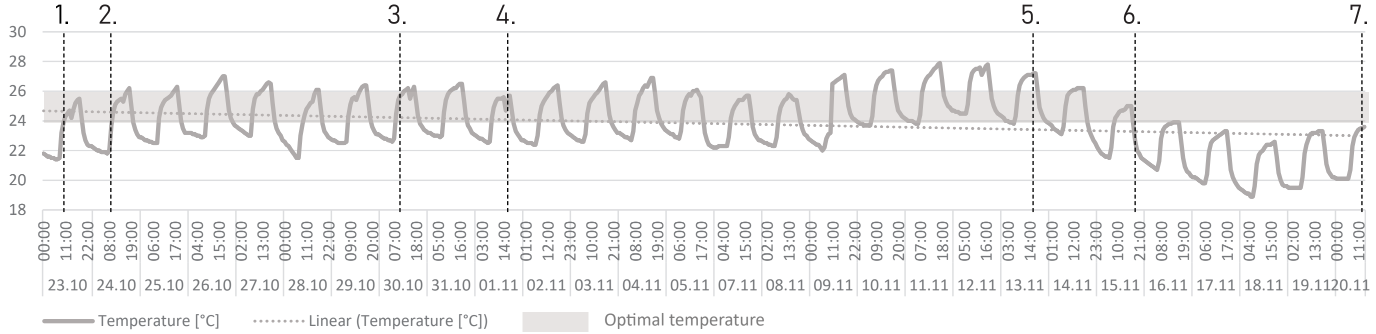


Figure 31. Temperature diagram during experiment 4 (Based on information provided from the app 'AranetHome', own work)

4.4.6 Temperature diagram

As the moulds were not all ready at the same time, the experiments began at different points in time. Additionally, the experiments reached their final stages at varying times, due to the differing rates of growth observed, which were dependent on the dimensions of the samples and the materials used.

1. Start growing process of compression samples: Hemp and sawdust with *Pleurotus ostreatus* and *Ganoderma lucidum*: CHP, CHG, CSP and CSG.
2. Start growing process of Compression samples: Cotton and jute with *Pleurotus ostreatus* and *Ganoderma lucidum*: CCP, CCG, CJP and CJG;
3. Start growing process Bending samples: Hemp, sawdust, cotton and jute with *Pleurotus ostreatus* and *Ganoderma lucidum*: BHP, BHG, BSP, BSG, BCP, BCG, BJP and BJG;
4. End of growing process compression samples: Hemp and sawdust with *Pleurotus ostreatus* and *Ganoderma lucidum*: CHP, CHG, CSP and CSG.
5. End of growing process compression samples: Cotton and jute with *Pleurotus ostreatus* and *Ganoderma lucidum*: CCP, CCG, CJP and CJG;
   End of growing process bending samples: Hemp with *Pleurotus ostreatus* and sawdust with *Pleurotus ostreatus* and *Ganoderma lucidum*. Hemp + *Ganoderma lucidum* was not fully grown yet.
6. A reduction in temperature was observed within the hotbox, which can be explained by the presence of colder weather conditions outside and the non-functioning radiator in the Faculty of Architecture.
7. The experiment was discontinued with the remaining bending samples. The mycelium development observed in the hemp sample was notably slow, and the cotton and jute samples remained in the form of loose material sheets with very poor tensile strength, rather than a single, intact sample.

4.4.7 Conclusion

In conclusion, the growth and development of the mycelium species *Pleurotus ostreatus* and *Ganoderma lucidum* showed notable differences across a range of substrates, highlighting the adaptability and challenges faced by each species.

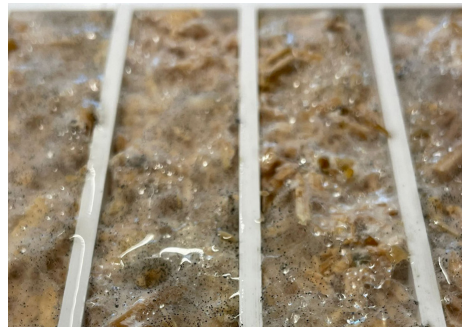
1. *Pleurotus ostreatus*
Pleurotus ostreatus demonstrated more consistent growth in general, particularly in compression samples, where it exhibited rapid development from day 3 onwards. Nevertheless, on occasion, external mould formation was observed in the samples of sawdust and cotton. However, in the case of the sawdust substrate, this external mould resolved itself spontaneously by day 12. Furthermore, this species demonstrated a tendency for surface growth, with minimal vertical growth through the layers of the woven cotton and jute substrates. This observation indicates that these materials may not provide optimal conditions for deeper mycelial growth with the *Pleurotus ostreatus* species.

2. *Ganoderma lucidum*
On the other hand, *Ganoderma lucidum* exhibited a slower initial growth rate, particularly in the woven cotton and jute substrates, where notable delays in development were observed. Nevertheless, when the mycelium did develop in the hemp and sawdust samples, it displayed resilience and accelerated growth in the later stages. The sawdust samples demonstrated the fastest final growth, even outperforming the *Pleurotus ostreatus*. It is noteworthy that the *Ganoderma lucidum* samples occasionally exhibited unusual surface changes, such as the development of yellow/orange-like moulds on the surface or pink discolouration. This suggests the potential for challenges in maintaining consistent growth or quality.

Both species demonstrated limited success in inoculating some substrates, particularly woven cotton and jute. This is likely due to pore size or the lack of suitable conditions for deeper mycelial colonization. The results indicate that while both *Pleurotus ostreatus* and *Ganoderma lucidum* have the potential to be valuable for mycelium-based materials, further optimisation of substrate characteristics and growth conditions would be necessary to achieve more homogeneous and efficient mycelial development. Consequently, future studies should focus on improving substrate compatibility and exploring alternative techniques to enhance the overall growth and application potential of these species in material fabrication. In the next experiment, both species will be tested to examine them further on their mechanical strength.

Cotton + *Pleurotus ostreatus* Day 20

Jute + *Ganoderma lucidum* Day 20



Hemp + *Pleurotus ostreatus* Day 3

Sawdust + *Ganoderma lucidum* Day 12

Three criteria for using fungal species:
Pleurotus ostreatus

1. Rate of growth:
Consistent and fast growing rate; ✔

2. Strong connections (hyphae):
Will be examined in the following chapter; ?

3. Resistance to external mould contamination:
Acceptable level of resistance. ✔

Three criteria for using fungal species:
Ganoderma lucidum

1. Rate of growth;
Not consistent, but accelerated growth in the later stages. ✔

2. Strong connections (hyphae);
Will be examined in the following chapter, but existing literature indicates that it has strong hyphae. ?

3. Resistance to external mould contamination.
Acceptable level of resistance. ✔

4.5
Mechanical strength testing

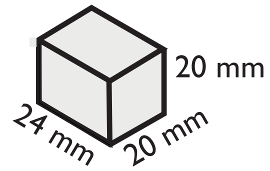
4.5 Mechanical strength testing

"What are the mechanical properties of mycelium-based composites consisting of these combinations and which combination perform best in terms of compression and three-point bending tests?"

4.5.1 Dimensions

1. Compression samples

Bio composites:
20 x 24 x 20 mm (Fred Veer)
< 100 kN



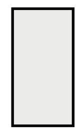
Explanation of dimensions
A cube of dimensions 20 x 24 x 20 mm, with a compressive strength of only 10 MPa, would require a load of 4000 N. The cube's size is determined by its compressive strength. The maximum load that can be applied is 80 kN, which represents 80% of the 100 kN range. Therefore, the objective is to find a cube that can withstand an 80 kN force.
(Appendix 8.1.8, row 4.1)

2. Bending samples

Bio composites:
4 point bending test: Length >120 mm
3 point bending test: 50 mm < length < 120 mm
1/10 length ≤ Height & Width ≤ 1/5 length

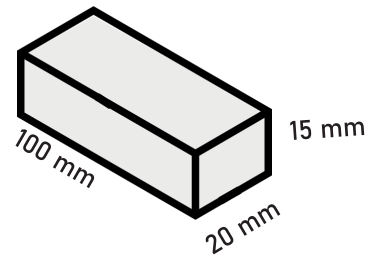
Height ≤ Width
when application is panel, floor, brick, roof, etc.

Height ≥ Width
when application is for example a beam or a bridge.



Dimensions using:

The final product will be a panel of block, so
Height ≤ Width
100 x 20 x 15 mm
(Appendix 8.1.8, row 4.1)



Numbers of samples for mechanical testing
(Appendix 8.1.8, row 4.1)

		Compression 20x24x20 mm	Bending 100x20x15 mm
Pleurotus Ostreatus	**Jute**	8	8
	Cotton	8	8
	Hemp	8	8
	Sawdust	8	8
Ganoderma Lucidum	**Jute**	8	8
	Cotton	8	8
	Hemp	8	8
	Sawdust	8	8
	Total	**64**	**64**

Test		Substrate	Fungi species	Size [b x l x h]	Temperature [°C]	Humidity level [%]	Light influence	Duration	Growth discription	Pressed?	Weight per piece day 1	Weight per piece last day	Density ρ [kg/m3]	Comments
Compression tests	1	**Hemp fibres**	*Pleurotus ostreatus* Grain Spawn	8x 20x24x20mm	21 - 27	47 - 63	Artificial light	12 days	Added flour (10% of the total weight) to give it a kickstart	Hand-pressed before growing process	23 - 25 g -7 (weight mould)=16 - 18 g / 8 = **2 - 2,25 g per piece**	12 g / 8 = **1,50 g per piece**	156,25	16 mm high after pressing, a few fibres stick out, further shape intact
		Hemp fibres	*Ganoderma lucidum* Hedelcomposite	8x 20x24x20mm	21 - 27	47 - 63	Artificial light	12 days	Added flour (10% of the total weight) to give it a kickstart	Hand-pressed before growing process	33 - 37 g - 7 (weight mould)= 26 - 30 g / 8 = 3,25 - **3,75 g per piece**	21 g / 8 = **2,625 g per piece**	273,44	16 mm high after pressing, a few fibres stick out, further shape intact
	2	**Oak Sawdust**	*Pleurotus ostreatus* Grain Spawn	8x 20x24x20mm	21 - 27	47 - 63	Artificial light	12 days	Added flour (10% of the total weight) to give it a kickstart	Hand-pressed before growing process	36 g - 7 (weight mould) = 29 g / 8 = **3,625 g per piece**	23 g / 8 = **2,875 g per piece**	299,48	14 mm high after pressing, completely collabsed
		Oak Sawdust	*Ganoderma lucidum* Hedelcomposite	8x 20x24x20mm	21 - 27	47 - 63	Artificial light	12 days	Added flour (10% of the total weight) to give it a kickstart	Hand-pressed before growing process	33 - 36 g - 7 (weight mould)= 26 - 29 g / 8 = **3,25 - 3,625 g per piece**	24 g / 8 = **3,00 g per piece**	312,5	15 mm high after pressing, few cracks
	3	**Jute**	*Pleurotus ostreatus* Grain Spawn	8x 20x24x20mm	21 - 28	47 - 63	Artificial light	20 days	Added flour (10% of the total weight) to give it a kickstart	Hand-pressed before growing process	16 - 17 g - 7 (weight mould) = 9 - 10 g / 8 = **1,125 - 1,25 g per piece**	7 g / 8 = **0,875 g per piece**	91,15	No vertical mycelium development, so not suitable for further testing
		Jute	*Ganoderma lucidum* Hedelcomposite	8x 20x24x20mm	21 - 28	47 - 63	Artificial light	20 days	Added flour (10% of the total weight) to give it a kickstart	Hand-pressed before growing process	21 g - 7 (weight mould) = 14 g / 8 = **1,75 g per piece**	6 g / 8 = **0,75 g per piece**	78,12	No vertical mycelium development, so not suitable for further testing
	4	**Cotton**	*Pleurotus ostreatus* Grain Spawn	8x 20x24x20mm	21 - 28	47 - 63	Artificial light	20 days	Added flour (10% of the total weight) to give it a kickstart	Hand-pressed before growing process	14 - 15 g - 7 (weight mould) = 7 - 8 g / 8 = **0,875 - 1 g per piece**	8 g / 8 = 1 **g per piece**	104,17	No vertical mycelium development, so not suitable for further testing
		Cotton	*Ganoderma lucidum* Hedelcomposite	8x 20x24x20mm	21 - 28	47 - 63	Artificial light	20 days	Added flour (10% of the total weight) to give it a kickstart	Hand-pressed before growing process	15- 18 g - 7 (weight mould) = 8 - 11 g / 8 = **1 - 1,375 g per piece**	7 g / 8 = **0,875 g per piece**	91,15	No vertical mycelium development, so not suitable for further testing
3 point bending tests	1	**Hemp fibres**	*Pleurotus ostreatus* Grain Spawn	8x 100x20x15mm	19 - 28	44 - 63	Artificial light	15 days	Added flour (10% of the total weight) to give it a kickstart	Hand-pressed before growing process	199 g - 96 (weight mould) = 103 g / 8 = **12,875 g per piece**	166 g - 96 = 70 g / 8 = **8,75 g per piece**	291,67	Mixture of substrate + mycelium + flour already made at 22.10.24 and saved in fridge
		Hemp fibres	*Ganoderma lucidum* Hedelcomposite	8x 100x20x15mm	19 - 28	44 - 63	Artificial light	15 days	Added flour (10% of the total weight) to give it a kickstart	Hand-pressed before growing process	236 g - 96 (weight mould) = 140 g / 8 = **17,5 g per piece**	N/A: Not fully grown	N/A	Mixture of substrate + mycelium + flour already made at 22.10.24 and saved in fridge
	2	**Oak Sawdust**	*Pleurotus ostreatus* Grain Spawn	8x 100x20x15mm	19 - 28	44 - 63	Artificial light	15 days	Added flour (10% of the total weight) to give it a kickstart	Hand-pressed before growing process	260 g - 96 (weight mould) = 164 g / 8 = **20,5 g per piece**	226 g - 96 = 130 g / 8 = **16,25 g per piece**	541,67	Mixture of substrate + mycelium + flour already made at 22.10.24 and saved in fridge
		Oak Sawdust	*Ganoderma lucidum* Hedelcomposite	8x 100x20x15mm	19 - 28	44 - 63	Artificial light	12 days	Added flour (10% of the total weight) to give it a kickstart	Hand-pressed before growing process	271 g - 96 (weight mould) = 175 g / 8 = **21,875 g per piece**	237 g - 96 = 141 g / 8 = **17,625 g per piece**	587,5	Mixture of substrate + mycelium + flour already made at 22.10.24 and saved in fridge
	3	**Jute**	*Pleurotus ostreatus* Grain Spawn	8x 100x20x15mm	19 - 28	41 - 63	Artificial light	20 days	Added flour (10% of the total weight) to give it a kickstart	Hand-pressed before growing process	150 g - 77 (mould) = 73 g / 8 = **9,125 g per piece**	N/A: Not fully grown	N/A	No vertical mycelium development, so not suitable for further testing
		Jute	*Ganoderma lucidum* Hedelcomposite	8x 100x20x15mm	19 - 28	41 - 63	Artificial light	20 days	Added flour (10% of the total weight) to give it a kickstart	Hand-pressed before growing process	160 g - 77 (mould) = 83 g / 8 = **10,375 g per piece**	N/A: Not fully grown	N/A	No vertical mycelium development, so not suitable for further testing
	4	**Cotton**	*Pleurotus ostreatus* Grain Spawn	8x 100x20x15mm	19 - 28	41 - 63	Artificial light	20 days	Added flour (10% of the total weight) to give it a kickstart	Hand-pressed before growing process	141 g - 77 (mould) = 64 g / 8 = **8 g per piece**	N/A: Not fully grown	N/A	No vertical mycelium development, so not suitable for further testing
		Cotton	*Ganoderma lucidum* Hedelcomposite	8x 100x20x15mm	19 - 28	41 - 63	Artificial light	20 days	Added flour (10% of the total weight) to give it a kickstart	Hand-pressed before growing process	145 g - 77 (mould) = 68 g / 8 = **8,5 g per piece**	N/A: Not fully grown	N/A	No vertical mycelium development, so not suitable for further testing

Figure 32. Framework for testing samples mechanical strength, own work

Density calculation:

ρ [kg/m3] = M [kg] / V [m3]
M = Mass
V = volume

Volume compression samples:
20 x 20 x 24 mm = 9.600 mm3
= 0,96 x 10^-4 m3

Volume bending samples:
100 x 15 x 20 mm = 30.000 mm3
= 0,3 x 10^-3 m3

4.5.2 Samples for testing

CHP1 - CHP8
= Compression Hemp *Pleurotus ostreatus*
6x
(CHP2 and CHP3 fractured during the process of removal from the mould).

CHG1 - CHG8
= Compression Hemp *Ganoderma lucidum*
8x

CSP1 - CSP8
= Compression Sawdust *Pleurotus ostreatus*
8x

CSG1 - CSG8
= Compression Sawdust *Ganoderma lucidum*
8x

These next samples were still not grown into a complete unit after 20 days due to lack of vertical connection, so it was not possible to use them for testing (see paragraph 4.5.3 on p. 69):

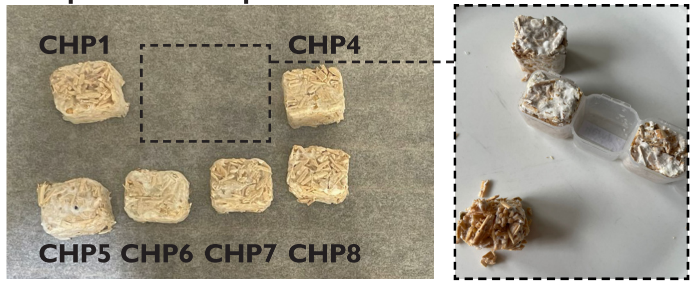
CCP1 - CCP8
= Compression Cotton *Pleurotus ostreatus*
0x

CCG1 - CCG8
= Compression Cotton *Ganoderma lucidum*
0x

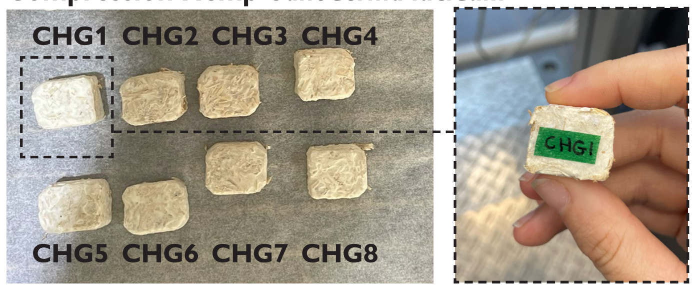
CJP1 - CJP8
= Compression Jute *Pleurotus ostreatus*
0x

CJG1 - CJG8
= Compression Jute *Ganoderma lucidum*
0x

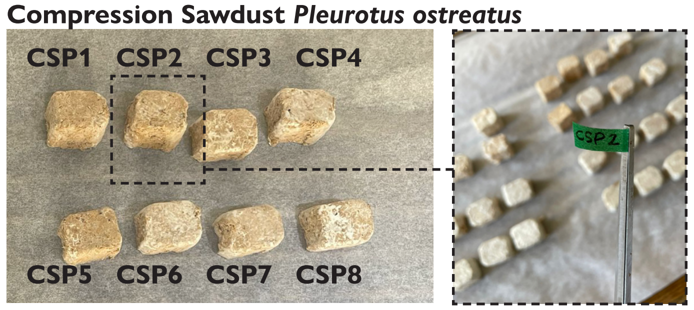
Compression Hemp *Pleurotus ostreatus*



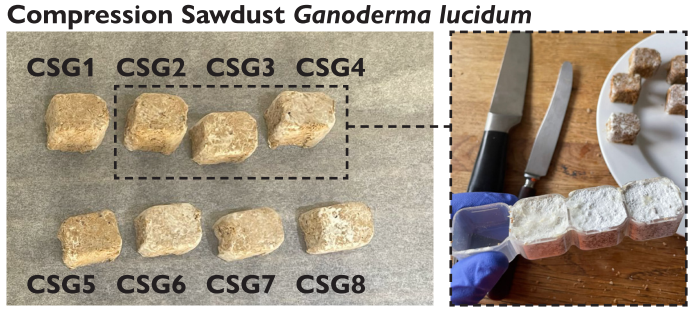
Compression Hemp *Ganoderma lucidum*



Compression Sawdust *Pleurotus ostreatus*



Compression Sawdust *Ganoderma lucidum*



Get sample out of the mould

→

2 days white skin development

→

Baking process: 4 hours 50°C

BHP1 - BHP8
= Bending Hemp *Pleurotus ostreatus*
8x

BHG1 - BHG8
= Bending Hemp *Ganoderma lucidum*
0x

The BHG-samples were still not fully grown after 20 days, resulting in the samples being unsuitable for testing.

BSP1 - BSP8
= Bending Sawdust *Pleurotus ostreatus*
8x

BSG1 - BSG8
= Bending Sawdust *Ganoderma lucidum*
8x

These samples were still not grown into a complete unit after 20 days due to lack of vertical connection, so it was not possible to use them for testing (see paragraph 4.5.3 on p. 69):

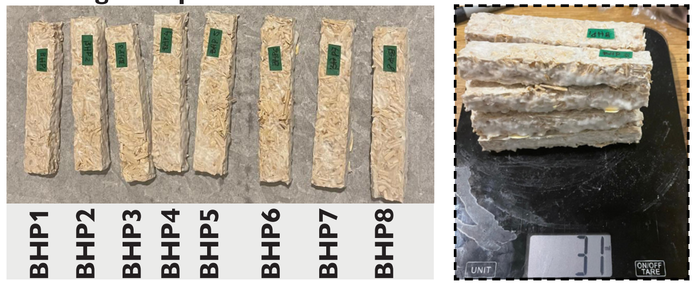
BCP1 - BCP8
= Bending Cotton *Pleurotus ostreatus*
0x

BCG1 - BCG8
= Bending Cotton *Ganoderma lucidum*
0x

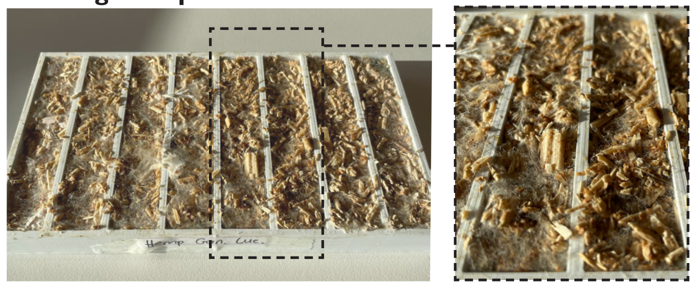
BJP1 - BJP8
= Bending Jute *Pleurotus ostreatus*
0x

BJG1 - BJG8
= Bending Jute *Ganoderma lucidum*
0x

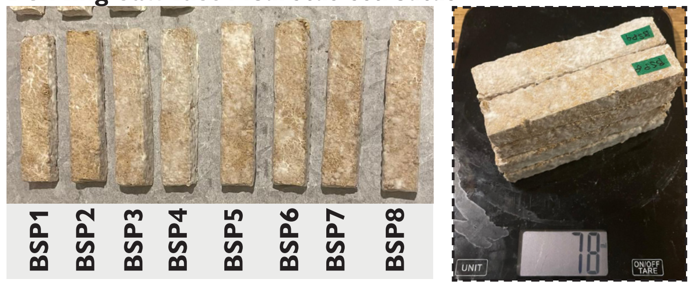
Bending Hemp *Pleurotus ostreatus*



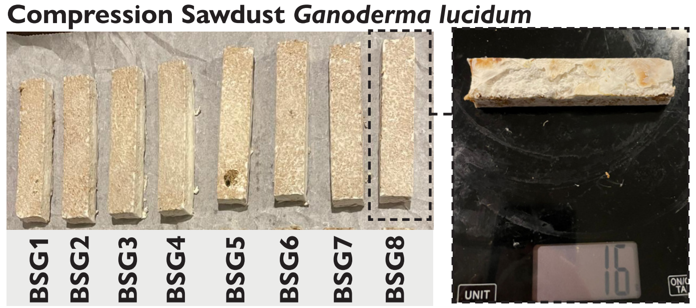
Bending Hemp *Ganoderma lucidum*



Bending Sawdust *Pleurotus ostreatus*



Compression Sawdust *Ganoderma lucidum*



4.5.3 Cotton & Jute samples

Due to the **absence** of **vertical hyphal connections** within the two substrates with the two mycelial species, it was decided that these samples would not be tested for compression and 3-point bending. The results of these tests would not be meaningful to include in the analysis, given the lack of interlayer connectivity and the consequent poor tensile strength. It can be concluded that the mechanical strengths of these two materials together with mycelium is the same as their mechanical strength without mycelium, since the mycelium is not binding or changing the properties of these substrates.

Cotton *Pleurotus ostreatus*

Jute *Pleurotus ostreatus*

Cotton *Ganoderma lucidum*

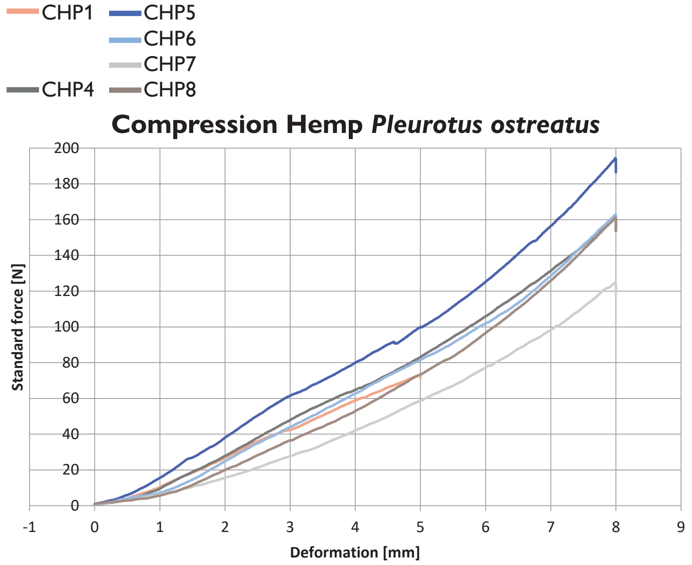
Jute *Ganoderma lucidum*

4.5.4 Compression tests

Substrates: Hemp or Sawdust

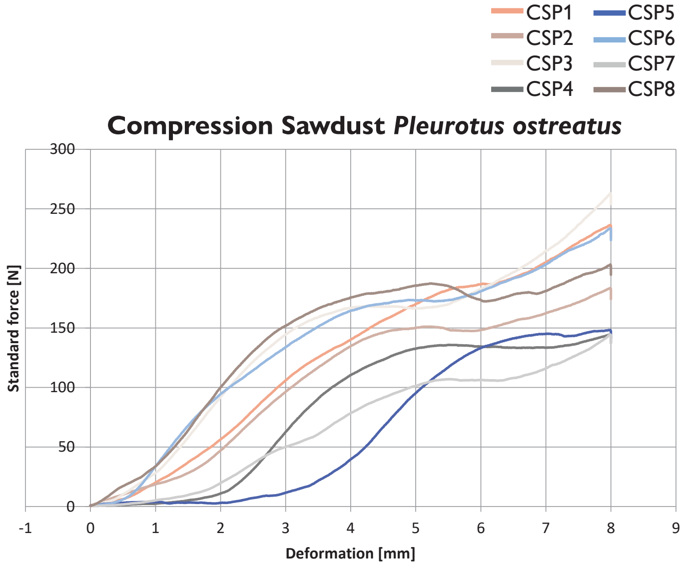
Fungal species: *Pleurotus ostreatus* & *Ganoderma lucidum*

Compression Hemp *Pleurotus ostreatus*

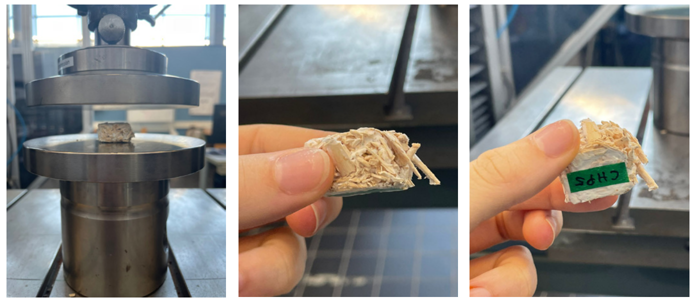


Maximum 194,4 N for 8 mm deformation

Compression Sawdust *Pleurotus ostreatus*



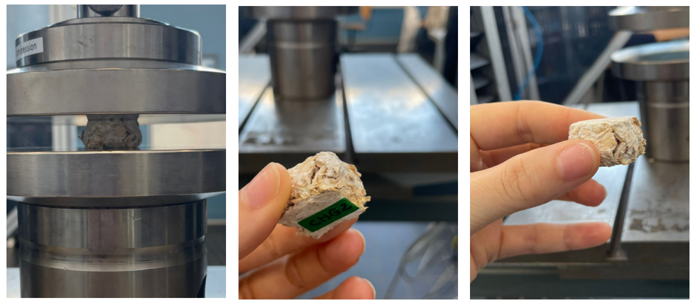
Maximum 263,1 N for 8 mm deformation



Hemp *Pleurotus ostreatus*

Sawdust *Pleurotus ostreatus*

Hemp *Ganoderma lucidum*

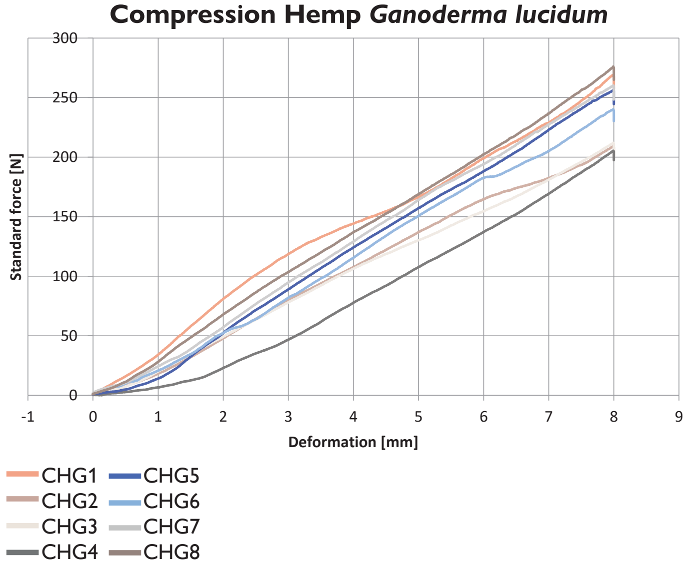


Maximum 256,1 N for 8 mm deformation

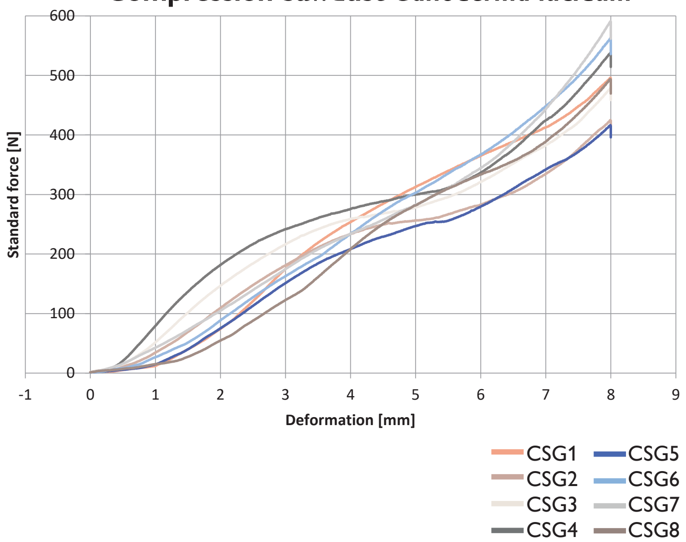
Sawdust *Ganoderma lucidum*

Maximum 591,0 N for 8 mm deformation

Compression Hemp *Ganoderma lucidum*



Compression Sawdust *Ganoderma lucidum*



Calculations stiffness (Young's modulus / Elastic modulus E)

		Formula	Formula applied	Quantity	Unit
A	**Area A**	A [mm2] = Width [mm] x Length [mm]	24 * 20 mm	48	mm2
ΔL	**Total deformation**			8	mm
L0	**Total length**			20	mm
ε	**Strain**	ε = (ΔL pt.2 / height) [mm] - (ΔL pt. 1 / height) [mm]	(4/20) - (2/20)	0,1	
σ	**Stress**	σ [N/mm2] or [MPa] = load [N] / area [mm2]			
E	**Elastic modulus**	E [MPa] = σ [MPa] / ε			

	Sample number	Linear trendline formula	F2 [N]	F2 / A [N/mm2]	F4 [N]	F4 / A [N/mm2]	σ [MPa]	E [MPa]	Mean E [MPa]
Hemp *Pl. ostr.*	**CHP1**	y = 15,396x - 3,4288	27,34	0,57	58,06	1,21	0,64	6,4	
	CHP4	y = 19,932x - 10,844	29,02	0,6	68,88	1,43	0,83	8,3	
	CHP5	y = 23,227x - 8,8501	37,02	0,78	84,05	1,75	0,97	9,67	
	CHP6	y = 19,934x - 13,209	26,66	0,56	66,53	1,39	0,83	8,31	
	CHP7	y = 15,387x - 13,043	17,73	0,37	48,51	1,01	0,64	6,41	
	CHP8	y = 19,743x - 17,552	21,93	0,46	61,42	1,28	0,82	8,23	7,89
Hemp *Gan. luc.*	**CHG1**	y = 31,853x + 10,737	74,43	1,55	138,17	2,88	1,33	13,28	
	CHG2	y = 27,236x - 3,9454	50,52	1,05	105,01	2,19	1,14	11,35	
	CHG3	y = 26,607x - 3,4679	49,74	1,04	102,97	2,15	1,11	11,09	
	CHG4	y = 26,988x - 24,218	29,76	0,62	83,73	1,74	1,12	11,24	
	CHG5	y = 33,642x - 12,686	54,58	1,14	121,93	2,54	1,4	14,03	
	CHG6	y = 30,968x - 8,1679	53,76	1,12	115,72	2,41	1,29	12,91	
	CHG7	y = 33,463x - 6,3097	60,59	1,26	127,59	2,66	1,4	13,96	
	CHG8	y = 34,32x - 2,256	66,38	1,38	135,05	2,81	1,43	14,31	12,77
Sawdust *Pl. ostr.*	**CSP1**	y = 30,869x + 1,4605	63,18	1,31	124,98	2,6	1,29	12,88	
	CSP2	y = 23,95x + 10,111	58,04	1,21	105,96	2,21	1	9,98	
	CSP3	y = 29,222x + 23,226	81,84	1,7	140,18	2,92	1,22	12,16	
	CSP4	y = 22,717x - 8,7262	36,61	0,76	82,1	1,7	0,94	9,48	
	CSP5	y = 24,062x - 32,985	14,71	0,31	63,09	1,31	1,01	10,08	
	CSP6	y = 27,278x + 27,447	82,39	1,72	136,77	2,85	1,13	11,33	
	CSP7	y = 19,113x - 8,3211	29,74	0,62	68,08	1,41	0,79	7,99	
	CSP8	y = 23,52x + 43,689	91,6	1,91	138,17	2,88	0,97	9,7	10,45
Sawdust *Gan. luc.*	**CSG1**	y = 65,855x - 32,258	98,6	2,05	230,98	4,81	2,76	27,58	
	CSG2	y = 49,358x + 7,5135	106,43	2,22	204,94	4,27	2,05	20,52	
	CSG3	y = 53,677x + 21,189	129,23	2,69	235,95	4,92	2,23	22,23	
	CSG4	y = 56,813x + 35,02	150,18	3,13	261,81	5,45	2,32	23,26	
	CSG5	y = 52,35x - 19,482	84,53	1,76	189,63	3,95	2,19	21,9	
	CSG6	y = 70,439 x - 43,093	96,58	2,01	237,25	4,94	2,93	29,31	
	CSG7	y = 68,505x - 32,53	104,72	2,18	238,04	4,96	2,78	27,78	
	CSG8	y = 64,209x - 50,73	75,69	1,58	204,88	4,27	2,69	26,92	24,94

Figure 33. Calculation-table Young's Modulus, own work

Low Young's Modulus: more flexible rubber-like material

Higher Young's Modulus: stiffer material

x = Deformation [mm]
y = Force [N]
F2 = Force (y) on deformation 2 (x = 2 mm)
F4 = Force (y) on deformation 4 (x = 4 mm)

Young's modulus or Elastic modulus

When an external force, or better known as stress, is applied to an elastomer, it will change its shape (strain). The young's modulus or elastic modulus is defined as the ratio of stress to strain.

The Young's Modulus is a measure of a material's resistance to elastic deformation.

A higher value indicated that a greater stress is required to produce a specific amount of elastic deformation, the greater the stress required to produce a certain amount of elastic deformation, meaning that the material is stiffer and experiences less elastic deformation under a given stress.

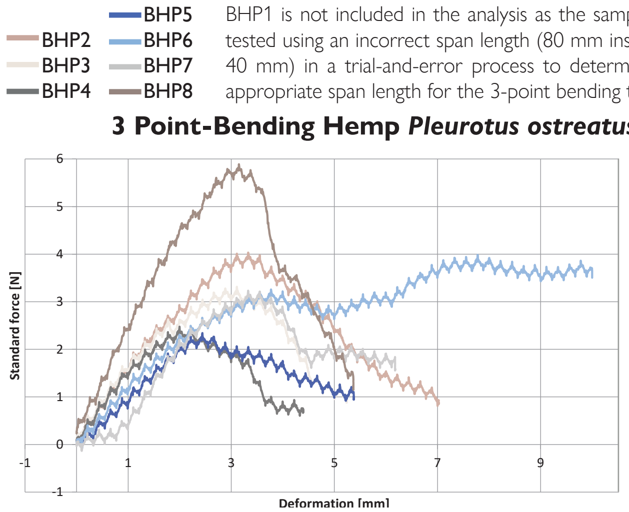
4.5.5 Three-point bending tests

Substrates: Hemp & Sawdust

Fungal species: *Pleurotus ostreatus* & *Ganoderma lucidum*

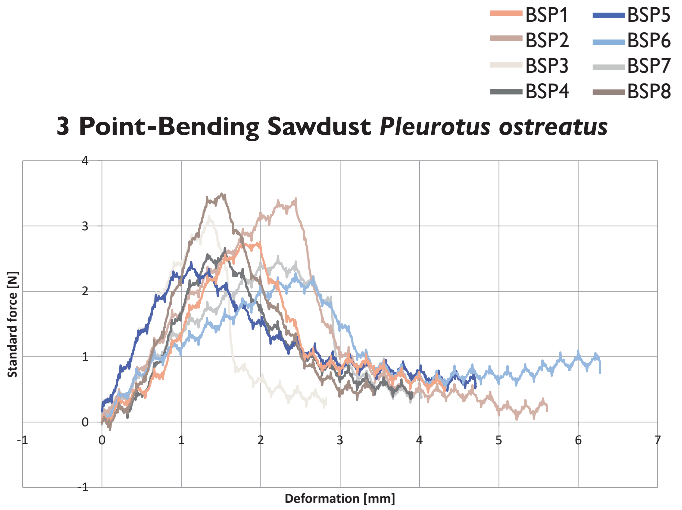
BHP1 is not included in the analysis as the sample was tested using an incorrect span length (80 mm instead of 40 mm) in a trial-and-error process to determine the appropriate span length for the 3-point bending test.

3 Point-Bending Hemp *Pleurotus ostreatus*



Maximum 5,75N for 3,2 mm deformation

3 Point-Bending Sawdust *Pleurotus ostreatus*



Maximum 3,5N for 1,5 mm deformation

Hemp *Pleurotus ostreatus*

Sawdust *Pleurotus ostreatus*

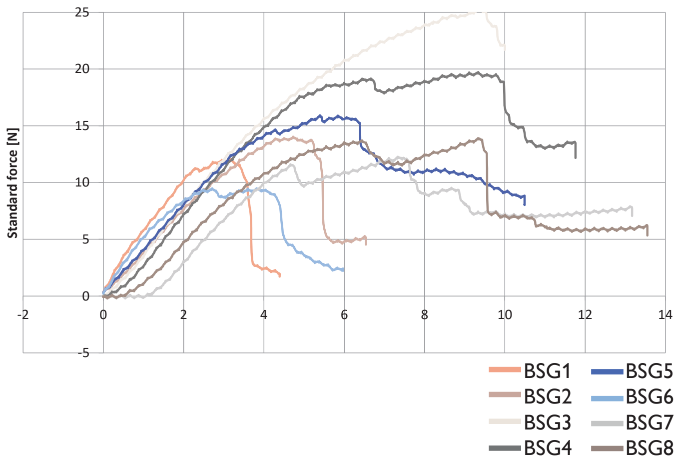
Hemp *Ganoderma lucidum*

After 20 days of growing still not fully grown. Accordingly, this combination is to be excluded from the bending test.

Sawdust *Ganoderma lucidum*

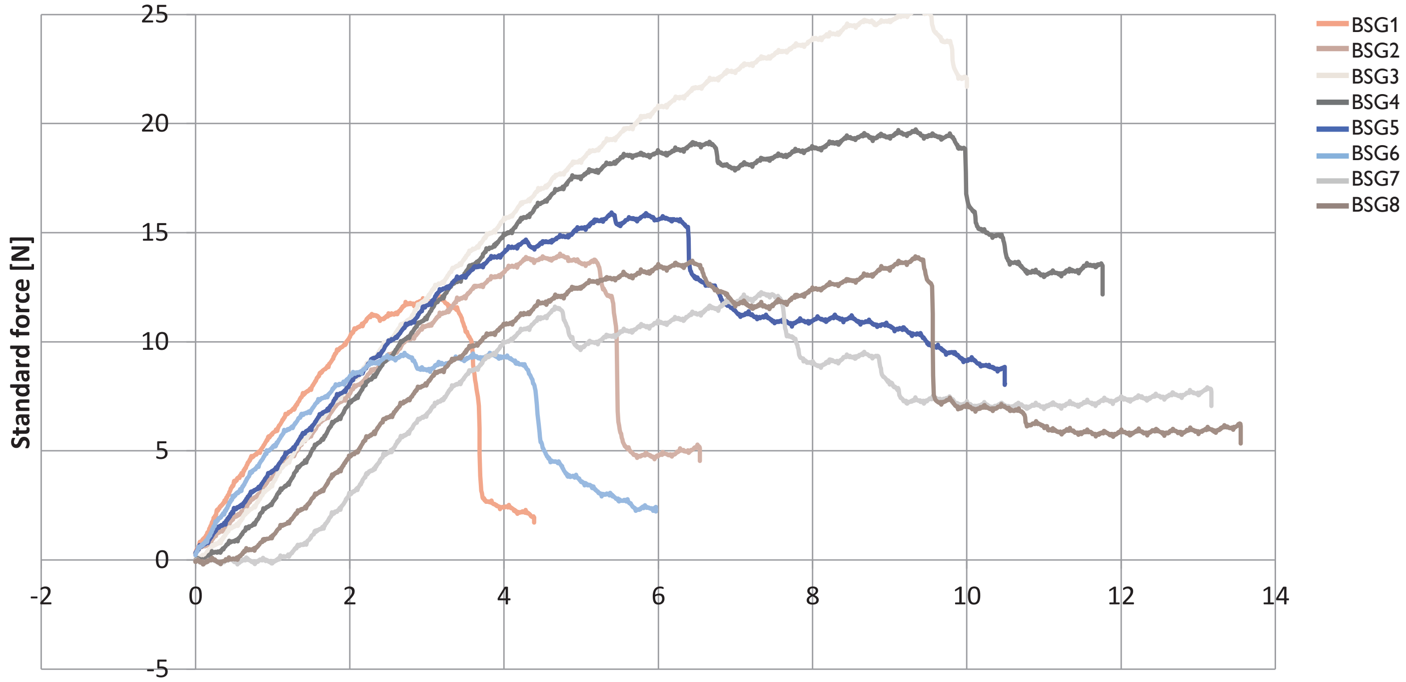
Maximum 25N for 9,5 mm deformation

3 Point-Bending Sawdust *Ganoderma lucidum*



Bending test | Sawdsut *Ganoderma lucidum*

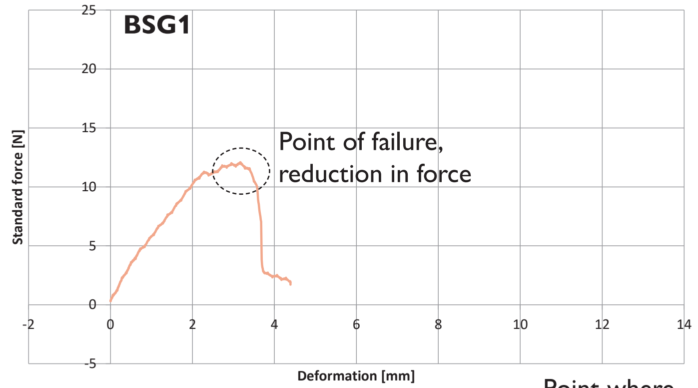
Different behaviour per sample



Divergent results: other distribution per sample. Three remarkable examples:

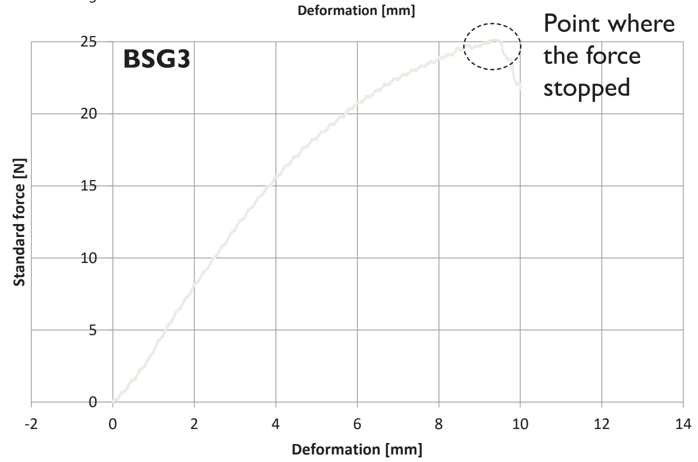
BSG1

Weak material (broke already at 3 mm deformation with 12 N), also not tough. When there was a crack occuring, the material broke very quickly, so it was very fragile.



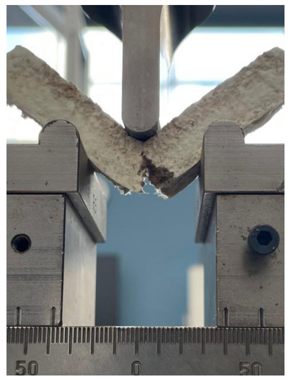
BSG3

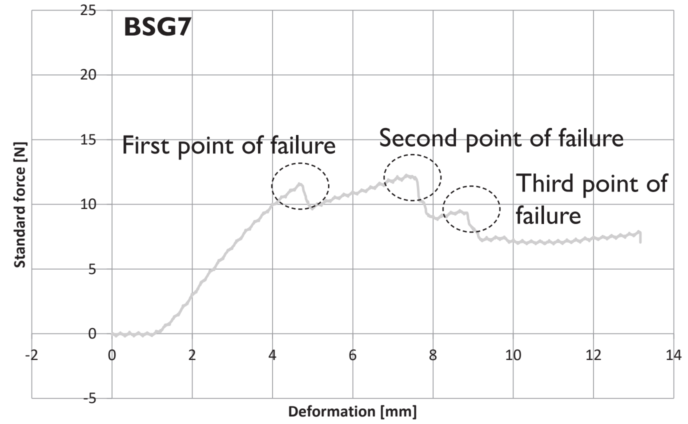
Most flexibe sample, only sample that did not break with high deformation (almost 10 mm) and highest force (25 N).



BSG7

Progressive course, not too strong material (maximum 12,5 N) but high delay mechanism. There was a quick breaking point (already with 4,5 mm deformation) but the material fibers kept the sample together as long as possible (tough sample), so the material acts as a delayer, preventing the complete collapse.





Calculations bending tests

		Formula	Formula applied	Quantity	Unit
l	**Span**			40	mm
p	**Load**				N
M	**Bending moment**	(pl/4)	(p*40) / 4		Nmm
σ	**Stress**	σ [N/mm2] or [MPa] = load [N] / area [mm2] σ max = 6M / bd^2 bd^2 = 20 mm * 15 mm^2 = 4500 mm^3	 6M / 4500		[MPa]
E	**Elastic modulus**	E [MPa] = σ [MPa] / ε			

	Hemp *Pleurotus ostreatus*					Sawdust *Pleurotus ostreatus*					Sawdust *Ganoderma lucidum*				
Sample number	**Maximum strength [N]**	**Standard Deviation [N]**	**Maximum moment [Nmm]**	**Maximum stress σ [MPa]**	**Standard Deviation [MPa]**	**Maximum strength [N]**	**Standard Deviation [N]**	**Maximum moment [Nmm]**	**Maximum stress σ [MPa]**	**Standard Deviation [MPa]**	**Maximum strength [N]**	**Standard Deviation [N]**	**Maximum moment [Nmm]**	**Maximum stress σ [MPa]**	**Standard Deviation [MPa]**
1	-	-	-	-	-	2,54	0,31	25,4	0,03	0,01	12,09	3,16	120,9	0,16	0,05
2	4,03	0,44	40,3	0,05	0	3,42	0,57	34,2	0,05	0,01	14,04	1,21	140,4	0,19	0,02
3	3,32	0,27	33,2	0,04	0,01	3,15	0,3	31,5	0,04	0	25,33	10,08	253,3	0,34	0,13
4	2,48	1,11	24,8	0,03	0,02	2,66	0,19	26,6	0,04	0	19,74	4,49	197,4	0,26	0,05
5	2,27	1,32	22,7	0,03	0,02	2,45	0,4	24,5	0,03	0,01	15,93	0,68	159,3	0,21	0
6	3,92	0,33	39,2	0,05	0	2,28	0,57	22,8	0,03	0,01	9,5	5,75	95	0,13	0,08
7	3,23	0,36	32,3	0,04	0,01	2,81	0,04	28,1	0,04	0	12,28	2,97	122,8	0,16	0,05
8	5,89	2,3	58,9	0,08	0,03	3,5	0,65	35	0,05	0,01	13,92	1,33	139,2	0,19	0,02
Mean	3,59	0,88	35,91	0,05	0,01	2,85	0,38	28,51	0,04	0,01	15,25	3,71	153,54	0,21	0,05

Figure 34. Calculation-table Maximum stress, own work

Standard deviation: $s = \sqrt{\frac{\sum(x - \bar{x})^2}{n - 1}}$

A standard deviation (σ) is a statistical measure that quantifies the distribution of data points around a given mean. A low standard deviation indicates that the data are grouped closely around the mean, whereas a high standard deviation suggests that the data are separated from the mean to a greater spread of the data.

In the case of both hemp Pleurotus ostreatus and sawdust Pleurotus ostreatus, the standard deviation of the maximum strength within the different samples is relatively low (mean = 0.88 N and 0.38 N, respectively). The standard deviation of the maximum strength for the sawdust Ganoderma luc. samples is considerably higher, with a mean of 3.71. This indicates that the data for this sample are more spread out. This could be attributed to the more even distribution of the material per sample within the samples with the first two mixtures. Alternatively, the higher number of strength values in the last mixture may also contribute to the increased absolut dispersion.

Sawdust + *Ganoderma lucidum*

Strongest combination, but not comparable to construction materials

Diverse results in testing, unsure about the distribution and properties

4.5.6 Conclusion

The testing of mechanical strength in 4.5 revealed that mycelium-based composites made from sawdust and *Ganoderma lucidum* performed best in terms of both compression and three-point bending tests. These samples demonstrated a higher resistance to compressive forces and greater stability during the bending process when compared to other combinations.

The findings highlight the significance of substrate and fungal species selection in optimising the mechanical properties of mycelium-based composites. The enhanced performance of the sawdust and *Ganoderma lucidum* combination can be attributed to its denser and more homogeneous structure, which is a key finding of this study.

In conclusion, sawdust and *Ganoderma lucidum* have been identified as the most effective mycelium-based composites for compression and bending, demonstrating their potential for non-structural, lightweight applications in sustainable building practices.

	Mechanical properties			Physical properties	
Material	**Compressive strength** [MPa]	**Tensile Strength** [MPa]	**Young's modulus** [GPa]	**Density** [kg/m^3]	**Source**
Concrete (insulating lightweight)	0,5 - 2,8	0,1 - 0,3	0,6 - 1,53	900 - 1,4e3	Granta EduPack 2023
High density concrete	30,6 - 36,6	3,1 - 3,7	40,2 - 41,6	4,9e3 - 5,5e3	Granta EduPack 2023
Low alloy steel, SAE 8630, cast, quenched & tempered	827 - 914	915 - 1,01e3	196 - 204	7,81e3 - 7,84e3	Granta EduPack 2023
Stainless steel, austentic, AMST CH-10, cast, water quenched	333 - 363	547 - 667	189 - 197	7,67e3 - 7,77e3	Granta EduPack 2023
Sawdust oak (l, quercus spp.)	68,2 - 83,3	133 - 162	20,6 - 25,2	850 - 1,03e3	Granta EduPack 2023
Sawdust oak (t, quercus spp.)	12,8 - 15,6	7,1 - 8,7	5 - 5.58	850 - 1,03e3	Granta EduPack 2023
Jute fiber	-	400 - 770	17 - 55	1,44e3 - 1,52e^3	Granta EduPack 2023
Mycelium composites	0,17 - 1,1	0,03 - 0,18	0,05e-3 - 0,29e-3*	59 - 552	(Jones et al., 2020)
MBC (sawdust + *Gan. luc.*)	*Not tested*	*Not tested*	0,025	299,48 - 587,5	Own experiments

Figure 35. Comparison table, own work

4.6
Microscopic research

4.6 Microscopic research

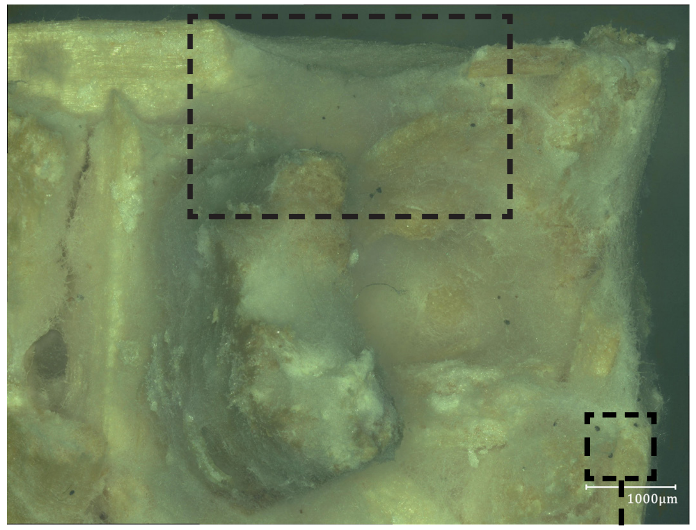
Following the completion of the 3-point bending tests, it became clear that the results exhibited a high degree of diversity. Consequently, it was necessary to investigate the distribution of the material within the various samples in order to gain a deeper understanding of the materials and their distribution across the samples. A digital 3D microscope was employed for this purpose, as it offers greater accuracy when examining non-flat surfaces, given the ability to capture detailed images of such surfaces.

4.6.1 Hemp *Pleurotus ostreatus* | BHP2

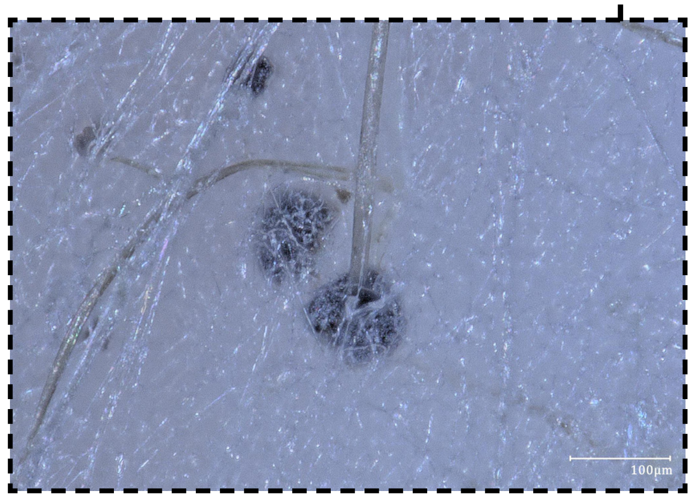
The distribution of the material is uneven, as evidenced by the image above, where only mycelium is visible, with no hemp present on this part of the material. Additionally, no hemp is visible beneath the layer of mycelium, indicating that this material sample includes some weak spots. A potential explanation for this problem is that the hemp particles are individual too large to be able to form a homogeneous sample within the specified dimensions of 100 x 20 x 15 mm.

Upon closer magnification of 500x, the small black dots appear to be external mould. As can be observed in the image on the right, the whiter thin mycelium threads are markedly different in texture, colour and thickness from the threads coming out of the external mould.

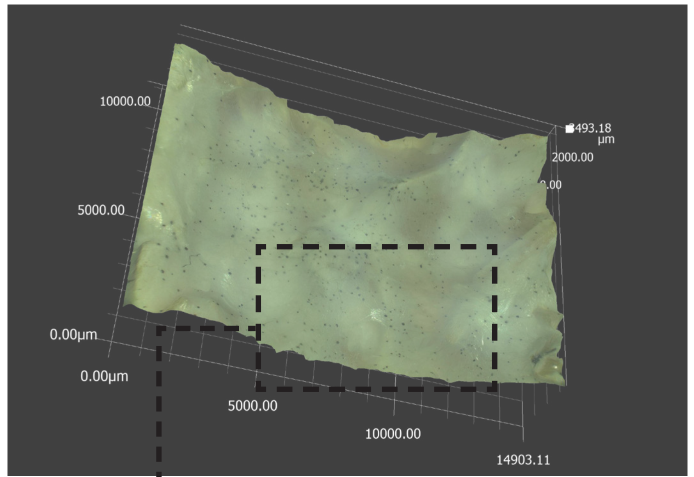
It is noteworthy that the surface reveals a greater number of black dots than the cross-section. This suggests that the external mould did not fully reach the centre of the sample, only the surface, potentially due to insufficient development. (Appendix 8.1.8, row 4.6)



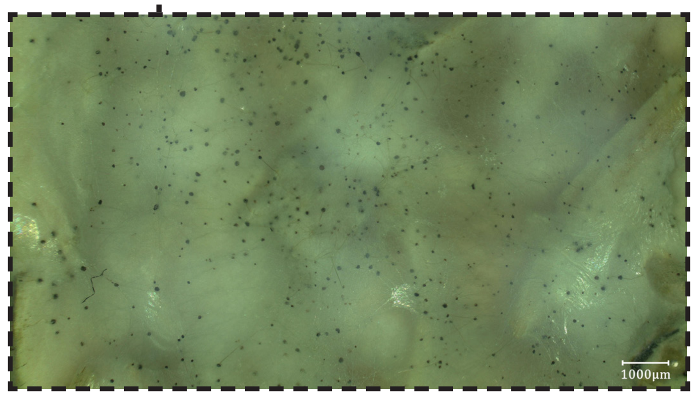
Cross section breaking point | 100x magnification



Cross section | Local black spot | 500x magnification



Surface | 50x magnification

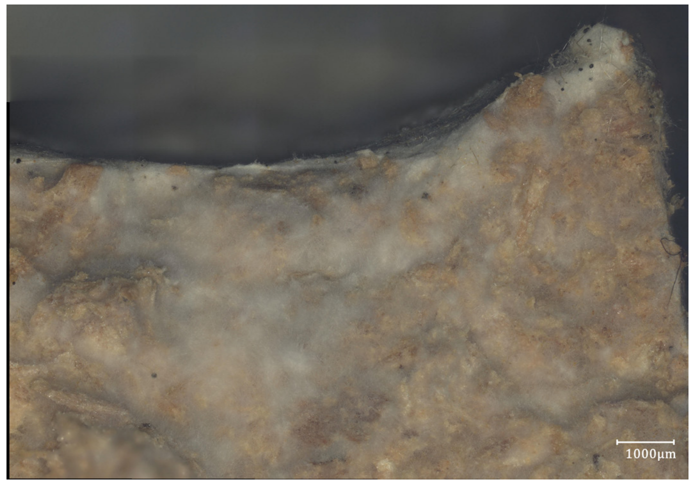


Surface | 50x magnification

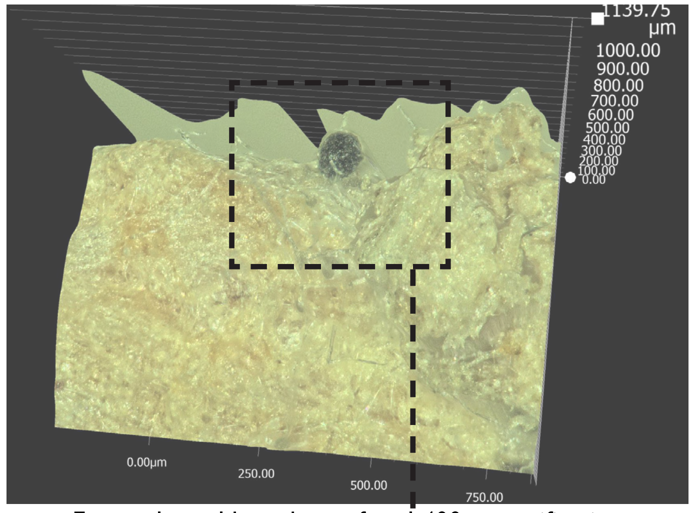
4.6.2 Sawdust *Pleurotus ostreatus* | BSP3

The distribution of the material is notably more homogeneous within this sample. Given that this mycelium species is the same as that observed on the previous page with the BHP sample, it is reasonable to conclude that the greater homogeneity of the distribution is a consequence of the use of a different substrate. The finer particles of sawdust, in comparison to the larger particles of hemp, are likely to have contributed to this outcome. This is clearly evident in the cross-section image above, wherein sawdust is observed to be distributed throughout the entire piece, situated beneath the layer of mycelium.

In the cross section, the black dots are barely visible, whereas on the surface, there are a considerable number of them. This indicates that the external mould did not fully reach the centre of the sample, only the outer layer, which may be due to insufficient development. In the second image, a localised black spot (external mould) on the surface is visible, showing how loose it is positioned on the surface, unable to enter the centre of the sample. Additionally, the third image illustrates the very thin mycelium threads on the outer layer searching for a connection. (Appendix 8.1.8, row 4.6)

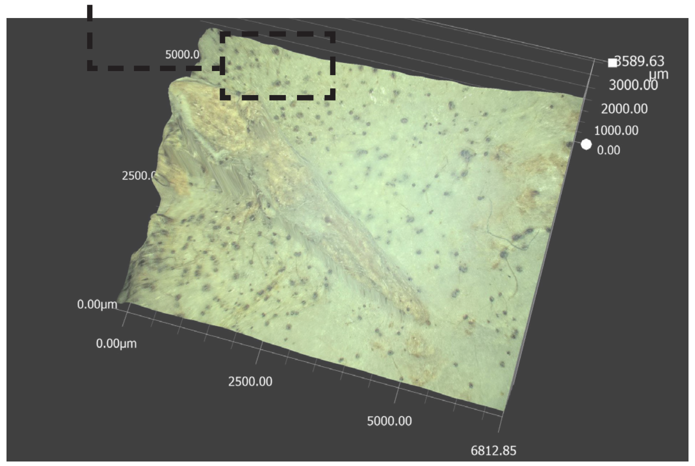


Cross section breaking point | 100x magnification

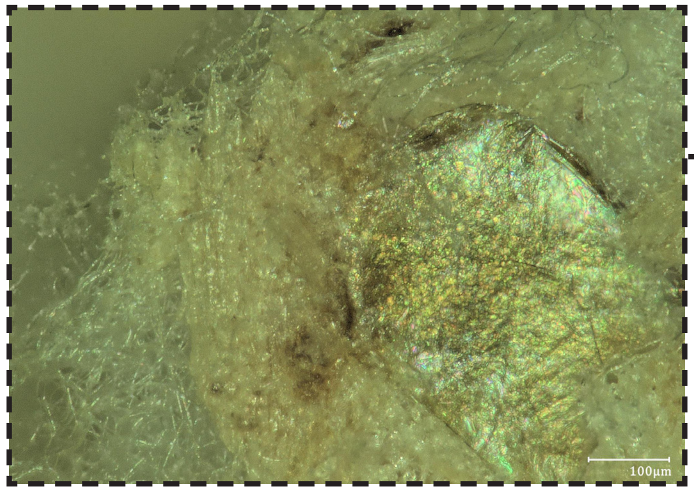


External mould on the surface | 400x magnification

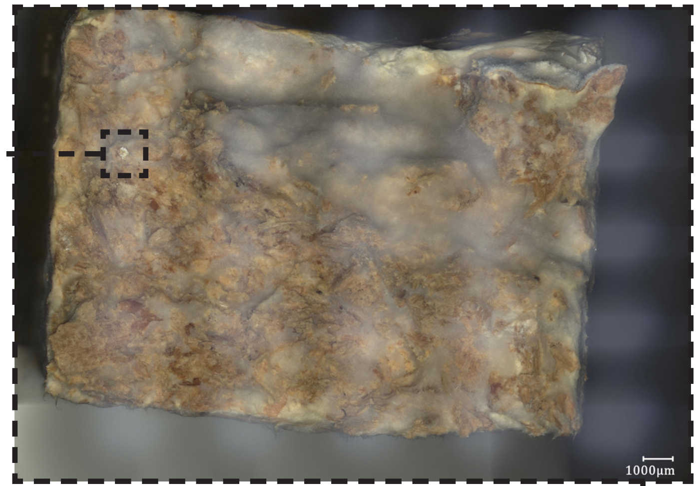
Surface | Local black spot | 400x magnification



Elevated sawdust particle on surface | 50x magnification



Cross section | shiny spot | 400x magnification



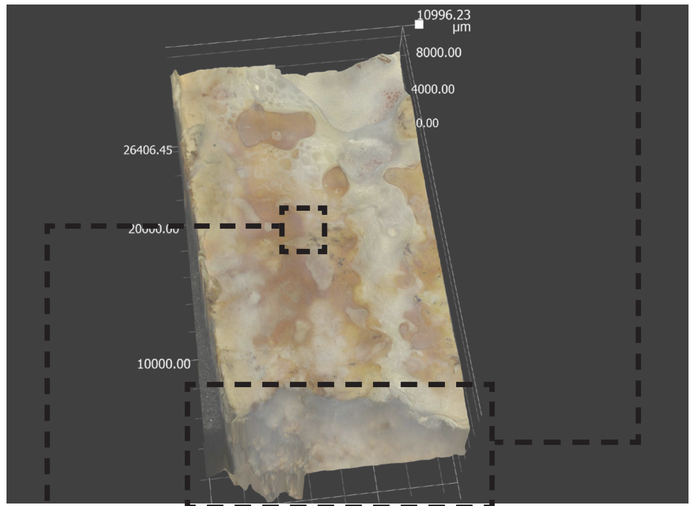
Cross section | 50x magnification

4.6.3 Sawdust *Ganoderma lucidum* | BSG3

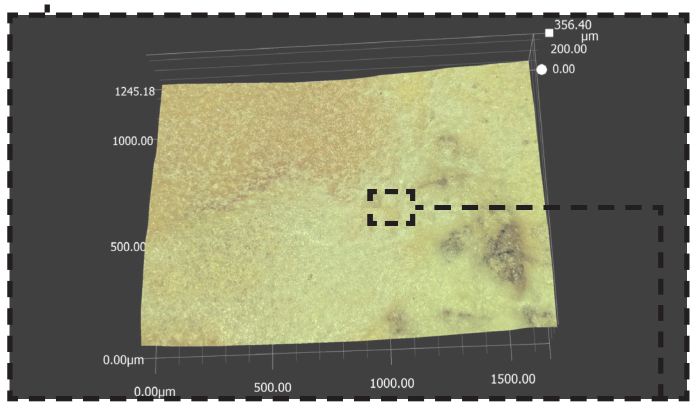
The selected sample was the one that demonstrated the greatest resilience to bending. BSG3 was the only sample that did not break, necessitating a closer examination of the distribution of this specific sample to identify the factors that contribute to its performance.

The image on the left top demonstrates a visible spot that appears to be shiny. However, closer examination reveals that it is actually composed of fine, thin layers of mycelium threads with minor contamination. The thin threads are clearly visible and appear to be seeking a connection. The image on the right top illustrates an optimal distribution of the substrate, which can be seen beneath the layer of mycelium.

It is notable that in the surface (50x magnification) there are barely any black dots, but there are other orange-ish areas visible. As can be seen in the bottom two images, this surface discolouration has the same fibrous structure and is only present on the outer layer of the sample, indicating that there is no depth contamination. However, it is possible that contamination with spores in the air may have occurred. It is not clear whether the discolouration areas have contributed to an improvement in the bending strength of the sample. To confirm this hypothesis, further testing would be necessary. (Appendix 8.1.8, row 4.6)



Surface with discolouration areas | 50x magnification



Surface | Local discolouration area | 200x magnification

Surface | Local discolouration area | 250x magnification

Surface | BSG3 | 50x magnification

4.6.4 Conclusion

In conclusion, the 3-point bending tests revealed a high degree of variability in the results, which led to the decision to conduct a more detailed examination of the material distribution. The examination of the chosen hemp with *Pleurotus ostreatus* sample (BHP2) revealed an uneven distribution of material, with mycelium present but exhibiting a lack of uniform integration with the loose hemp particles. The uneven distribution, potentially caused by the larger size of the hemp particles, resulted in the formation of weak points in the material, which were possibly a bit further weakened by the presence of external mould on the surface.

In contrast, the *Pleurotus ostreatus* samples with sawdust (BSP3) displayed a more uniform distribution, which was hypothesised to be due to the finer sawdust particles as substrate. The use of this substrate permitted a more even distribution of the mycelium threads, which may have resulted in enhanced overall stability. Also within this sample, there was some external mould present, although this mostly was visible on the surface, indicating that the mould had not penetrated deeply into the sample.

The sawdust-based Ganoderma lucidum sample (BSG3) exhibited the greatest resilience, demonstrating the highest resistance to bending without breakage. The distribution of the material in this sample was optimal, with a well-integrated substrate beneath a thin layer of mycelium. Although surface discolouration and minor contamination were observed, there was no evidence of deep contamination. There is a possibility that the sample's strength may have been influenced by its unique surface characteristics. The fact that this combination of sawdust and *Ganoderma lucidum* also had the best results with the compression tests without the discolouration could indicate that this discolouration is not the primary factor influencing the observed outcomes. Nevertheless, additional testing is necessary to ascertain whether this discolouration contributed to the enhanced bending performance.

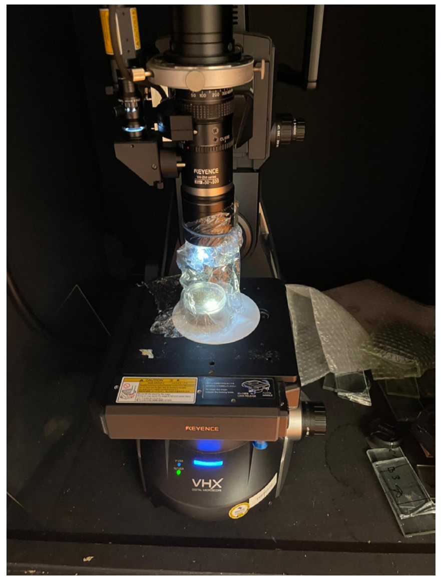
The results also highlight the significance of surface characteristics and contamination control in improving material strength and durability, thereby justifying further investigation into the potential impact of surface discolouration on bending strength.

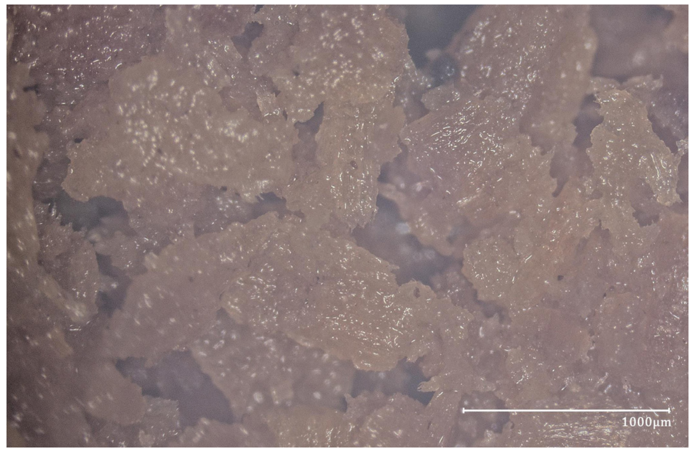
4.6.5 After conclusion: cultivation process

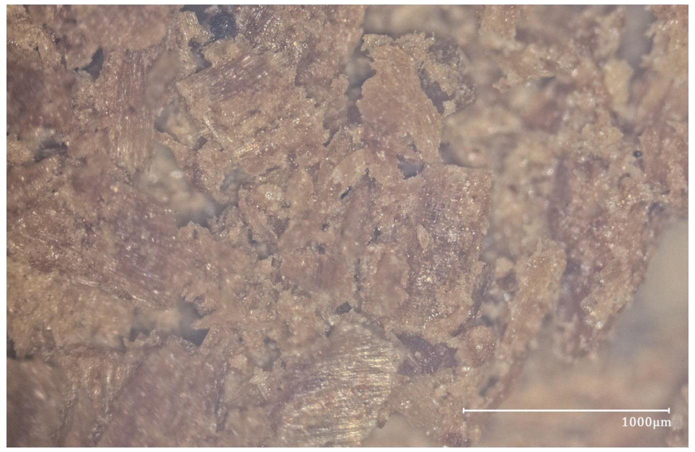
Following the determination that the combination of Ganoderma lucidum with sawdust exhibited optimal performance with regard to compression and three-point bending, the cultivation process of this particular combination was examined through the microscope. In order to prevent contamination during the growing process, a plastic foil was placed around the sample and the lens of the microscope (see picture below).

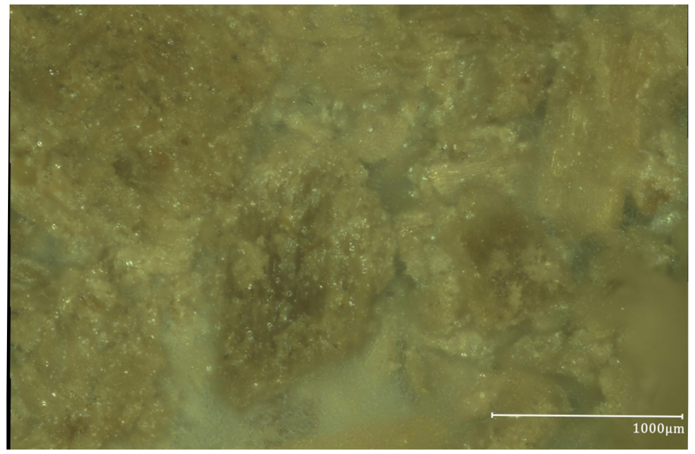
As illustrated in the time-lapse images (right), the hyphae demonstrates a notable delay in growth during the initial phase, but this process accelerates in the final days of the experiment. This observation aligns with the results previously observed in chapter 4.4: Fungal species comparison.

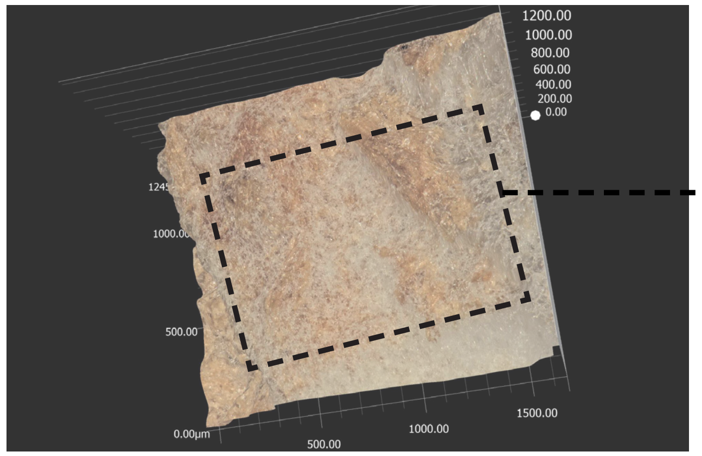
This investigation resulted in a three-dimensional representation of the development of mycelial hyphae.




Day 1 | 500x magnification


Day 5 | 500x magnification


Day 7 | 500x magnification


3D | Day 7 | 200x magnification


Day 7 | 200x magnification

05
Design & manufacture

"How can mycelium-based composite be designed and manufactured for a complex geometry building block for internal partitions?"

05 Design & manufacture

It is evident that mycelium-based composites possess favourable acoustic properties (Mogu.bio, 2024); however, their strength is insufficient for use as load-bearing building elements. Consequently, the most suitable building application is that of a partition wall, as this material functions optimally in interior environments. This is employed in an office environment, with the objective of creating acoustically pleasant spaces for meetings or telephone calls, with reduction of the reverberation time. The strongest combinations are selected in order to minimise material usage while maintaining the same level of mechanical strength. This approach not only minimises material usage but also optimises space utilisation within the floorplan, allowing for thinner partition walls.

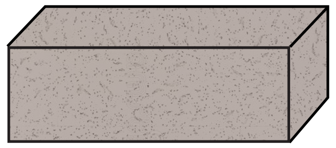
5.1 Manufacture

5.1.1 Without reinforced outer layers

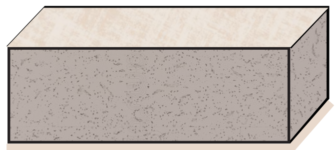
As demonstrated in Chapter 4, it becomes evident that the examined material samples vary significantly in composition (see pages 70 - 80). Additionally, the mechanical strength of these samples is not in comparison to that of traditional building materials (see Figure 35 on page 75). As stated in the reference to the Hy-Fi Pavilion in New York, mycelium-based composites were utilised, with the absence of reinforced tensile layers (p. 19). These blocks were arranged in a configuration similar to that of a Mansory wall; however, they appeared to lack the stability and rigidity necessary to withstand the forces of wind. Consequently, a wooden and steel scaffolding system was employed to provide support to the structure (Almpani-. Lekka et al., 2022)

5.1.2 With reinforced outer layers

In an investigation into enhancing the tensile strength and uniformity of the samples, jute is proposed as an outer layer Jute has previously been tested as a substrate in Chapter 4.3 on page 53, and it is evident that mycelium grows on it and external mould does not occur in significant amounts. Jute also has a tensile strength of between 400 and 700 MPa (see Figure 25, page 26). Furthermore, the added jute layers are beneficial in terms of the lower frequency levels, and thus contributes to an enhancement of the reverberation time (Appendix 8.1.7, interview 2, row 4.1).



Pure MBC panel: without reinforcement layers



Sandwich panel structure: with reinforcement layers

5.1.3 Mould

In the first experiment of this chapter, cardboard is cut and folded into the desired shape with a layer of wood glue applied and dried to prevent the mycelium from growing on the cardboard fibers. However, in practice, it is possible and more convenient to use a FlexiMould. Unfortunately, the FlexiMould from Dr. S

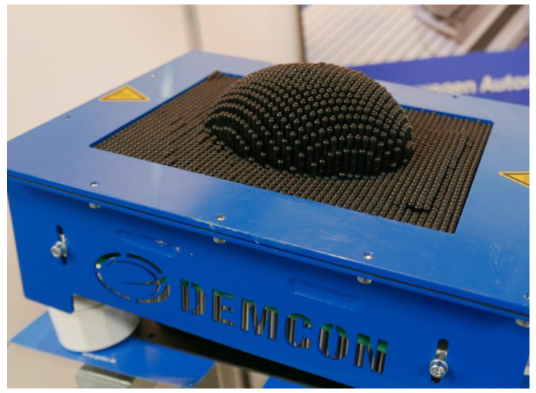


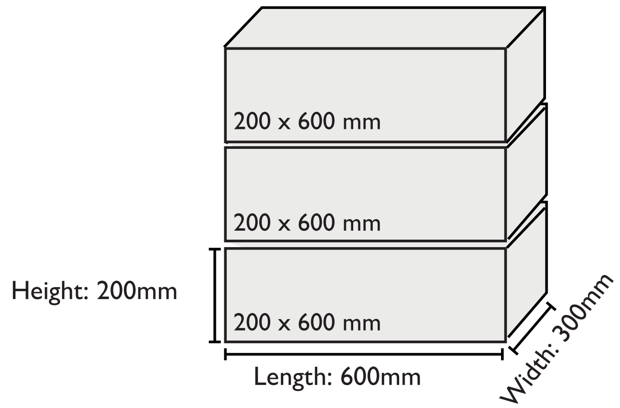
Figure 36. FlexiMould (Franc, 2018)

(Serdar) Aşut was disassembled, making it unavailable for use. In the concluding experiment, the fabrication of the final prototype involved the use of 3D printers to produce the mould, thereby allowing the creation of complex (corrugated) geometry.

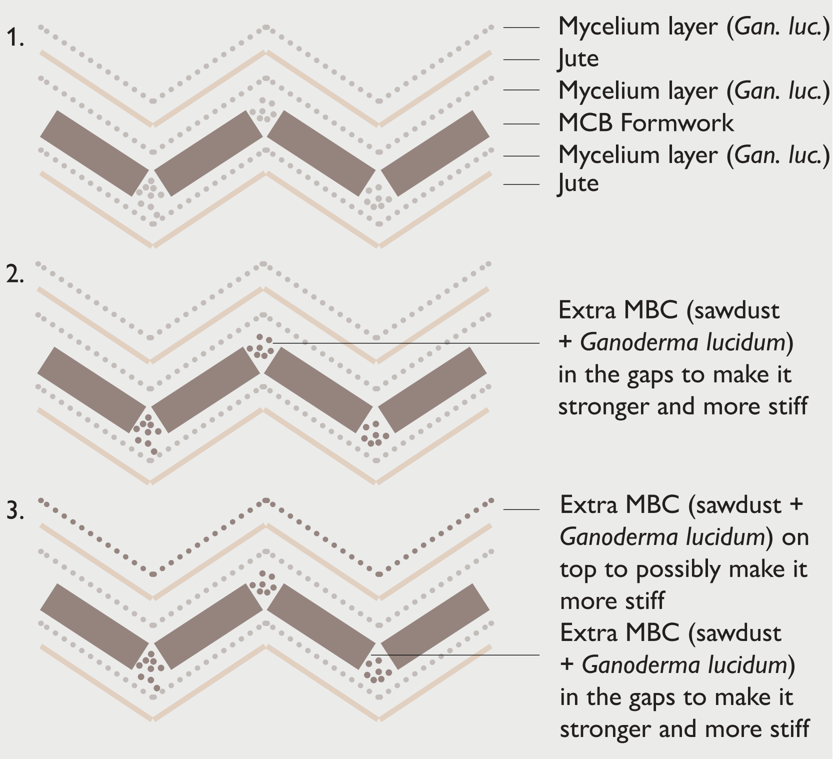
5.1.4 Dimensions of the blocks

The dimensions of the blocks are based on the dimensions of the Mogu panels on page 22, with a significantly higher thickness. The blocks have been designed to facilitate the repeated use of the same mould in order to construct a single layer of the partition wall.

In order to enhance the reverberation time in higer frequencies (Appendix 8.1.7, interview 2, row 4.1), the blocks will be manufactured in complex shapes, either ribbed or corrugated. Both options have been experimented with.



Configuration of prototype: Layering variants



5.1.5 Interlayer connections

Following the completion of the research, it became evident that the most innovative and homogeneous solution for the interlayer connection would be the use of mycelium, as this would result in a block composed entirely of a single primary material: mycelium. This approach not only enhances the blocks innovative character but also ensures it is 100% bio-based. However, the question remains whether mycelium alone is sufficiently rigid to maintain the complex shape and structural integrity of the block. In order to address this issue, two variants will be tested: V1 is with mycelium as the top layer and V2 is with MBC (sawdust + mycelium) as the top layer. The aim of this is to achieve greater structural stability while maintaining the material's sustainable and bio-based properties.

5.2 Experiment 6 | Prototype making

In the initial prototype, the ribbed, complex, structured shape has been selected for testing purposes. The objective of this test is to ascertain whether the configuration of layers will be sufficiently rigid to maintain its position following the final step of the growing process.

5.2.1 Formwork components

The new experiment involves a series of steps. The first step is the fabrication of the formwork components. It is crucial to ensure that the mycelium has not yet reached full growth before introducing it to the other layers of the panel, as this process allows the mycelium in the components to bind with the other layers, acting as a glue-like substance within the layers. It is therefore crucial to conduct regular observations of the samples to ascertain the growth rate. In Experiment 4, the sawdust + *Ganoderma lucidum* samples exhibited mycelial development after 10 days, leading to the assumption that a similar timeframe would be appropriate in the current experiment. However, the samples in Experiment 5 demonstrated mycelial development and the formation of a single unit that could be removed from the mould in only four days, a significantly faster process than observed in Experiment 4. This faster growth may be a consequence of the higher temperature within the hotbox.

5.2.2 Skin removal

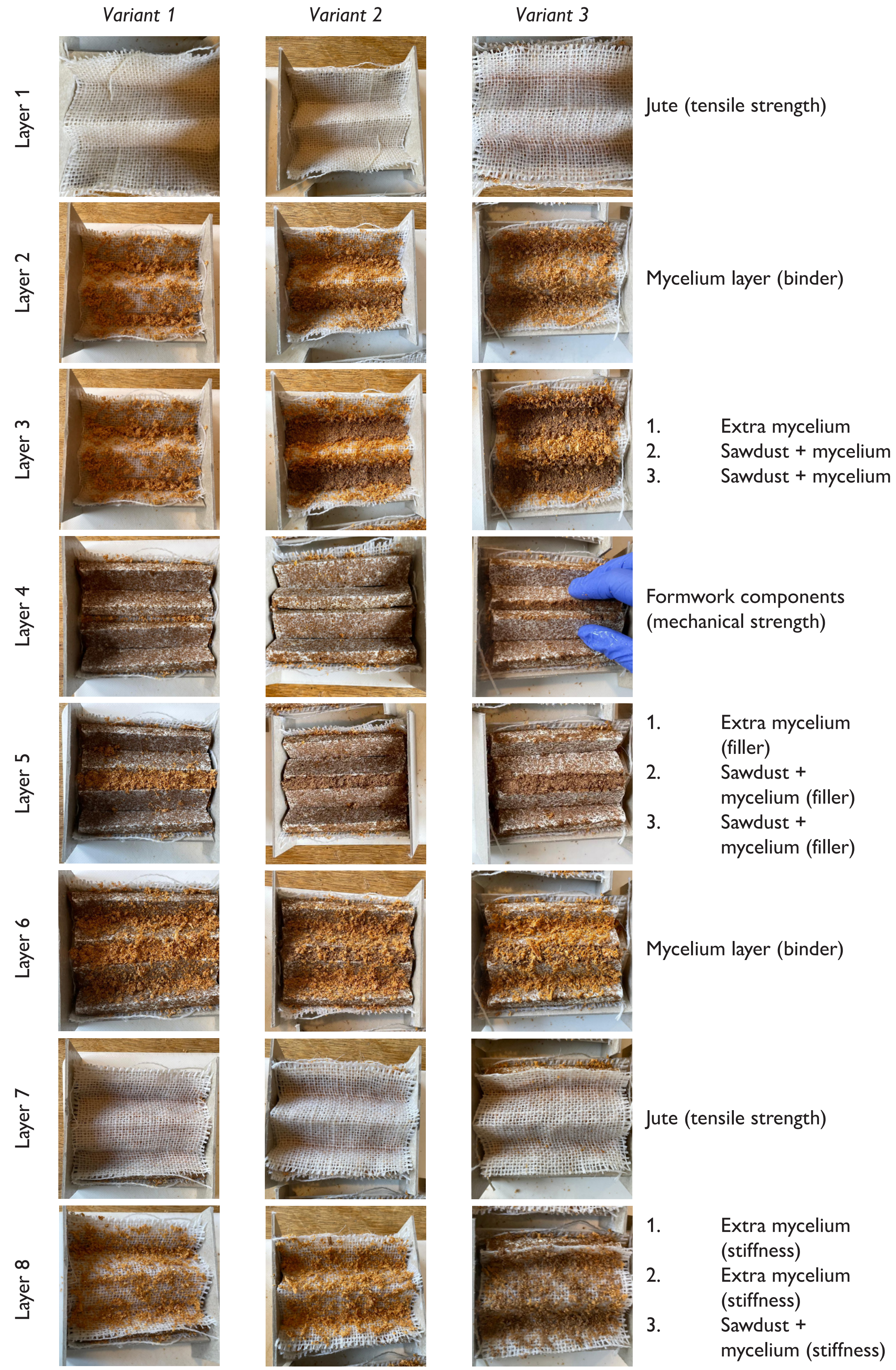
The components are removed from the hotbox and subsequently extracted from the mould with great care. The side exposed to the air has already formed a white skin, which must be removed in order to access the inner part that has not yet dried sufficiently. This process allows the mycelium to bind more effectively to the surrounding layers.

Day 1

Day 4

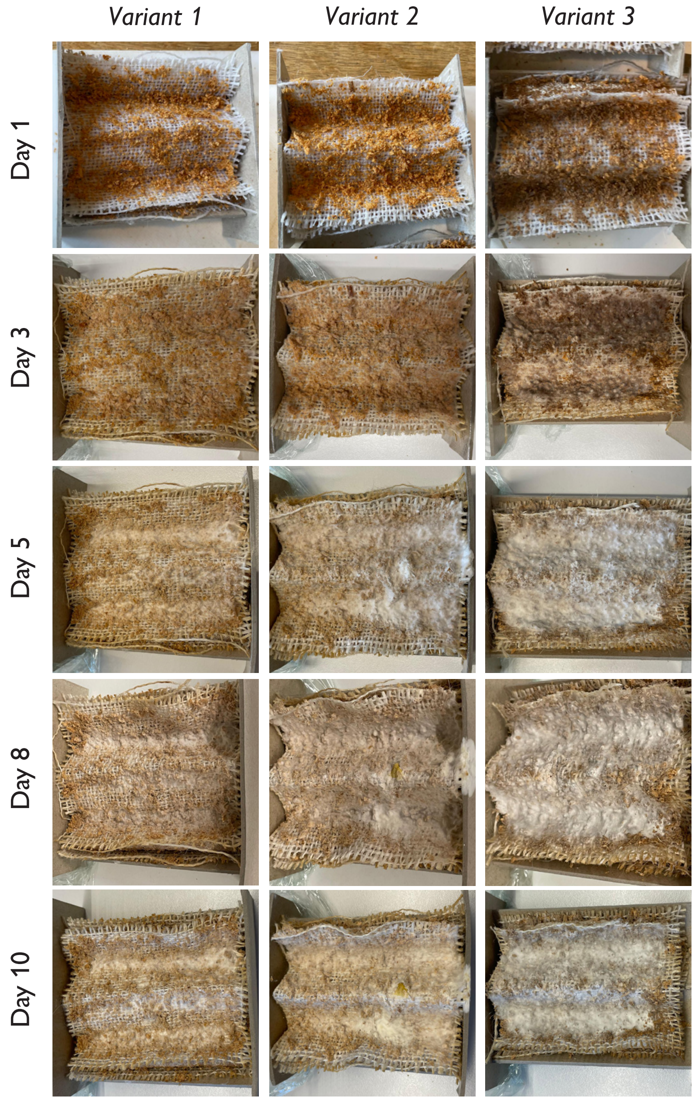
5.2.3 Layering

The three variants are now layered in the same order within the mould. The first two layers are identical across all variants. However, the third layer differs between the variants: variant 1 has this layer with only mycelium, while the other two variants have this layer consisting of sawdust + mycelium. The fifth layer is also identical, but the next filling layer differs between variants, with the same combination of layer 3. The sixth and seventh layers are identical, while the eighth layer differs between the variants. In variants one and two, the eighth layer is composed only of mycelium, whereas in the third variant, it is a combination of sawdust and mycelium.



5.2.4 Growing process

By the fifth day, mycelial development was observed on the surface of the panel. Visual observation indicated that variant 3 exhibited the most white appearance, suggesting that this panel with sawdust and mycelium on the top layer had the highest mycelial development on the surface. However, the internal structure and interactions between the layers cannot be fully observed. Nevertheless, seen from the side of the panel, it is notable that the mycelium appears to function as a binder, adhering the formwork components to the surrounding layers.



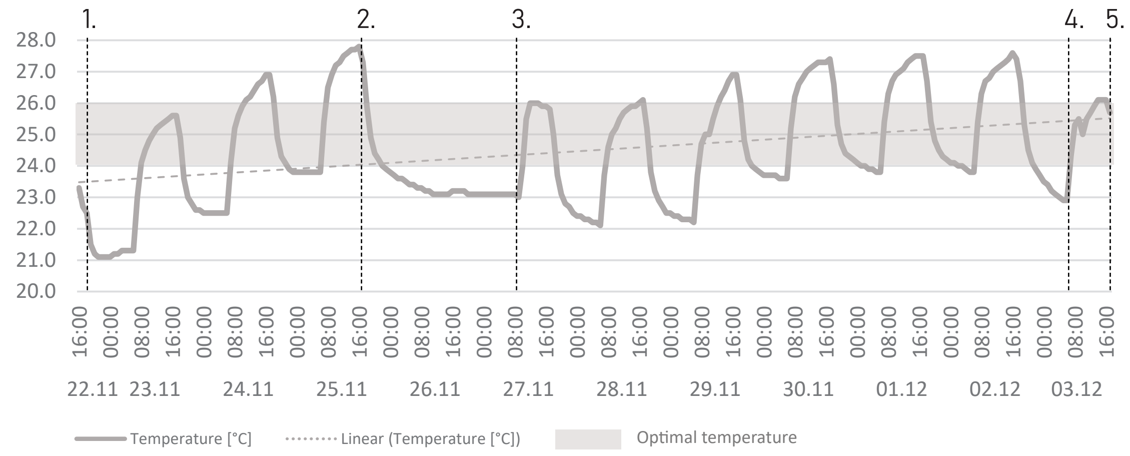


Figure 37. Temperature diagram during experiment 6 (Based on information provided from the app 'AranetHome', own work)

5.2.5 Temperature diagram

This experiment consisted of two phases: the first was the phase in which the formwork components were made and grew until they were not fully developed. The second phase was the phase in which the whole panel was made three times (including the components).

1. Start growing process of formwork components.
2. The formwork components are cultivated to a specific level, allowing for further growth while also reaching a degree of development that enables removal from the mould without the components collapsing.
   In order to save energy, the LED light source, which is the heat source for the hotbox, has been deactivated, as there is no longer a sample in the hotbox undergoing growth.
3. The three prototypes (panels) are placed within the hotbox, and the heat source is then reactivated to stimulate the growth of the samples.
4. Bending samples are places within the hotbox.
5. The prototypes are all being removed from the hotbox.

	Size [b x l x h]	Temperature [° C]	Humidity level [%]	Light influence	Duration	Growth discription	Pressed?	Weight per piece day 1	Weight per piece last day	Density ρ [kg/m3]
1	8x 100x20x15 mm	21 - 28	40 - 54	Artificial light	4 days	It lasted 4 days until the samples became one unit	Hand-pressed before growing process	149 g / 8 = **18,625 g per sample**	144 g / 8 = **18 g per sample**	600
2	4x 100x20x15 mm	21 - 28	40 - 54	Artificial light	4 days	It lasted 4 days until the samples became one unit	Hand-pressed before growing process	71 g / 4 = **17,75 g per sample**	67 g / 4 = **16,75 g per sample**	558,33
3	5x 100x20x15 mm	21 - 28	40 - 54	Artificial light	4 days	It lasted 4 days until the samples became one unit	Hand-pressed before growing process	95 g / 5 = **19 g per sample**	90 g / 5 = **18 g per sample**	600

Figure 38. Framework prototype components formwork, own work

5.3 Experiment 7 | Prototype testing

5.3.1 Layering

From a practical standpoint, it would be more efficient to produce the prototype samples with fewer steps. Therefore, the most logical approach would be to eliminate the step of growing the formwork components in another mould and forming them into a complete unit, and instead begin with the layering process, using the loose MBC mixture as a layer for the formwork instead of the already somewhat grown formwork components. This approach reduces the number of steps and effort required, as it eliminates the need for formwork production and growth in another mould, as well as cutting the skin. Additionally, it shortens the overall time by eliminating the removal of the skin.

Another advantage of this method is that it allows for the mycelium to remain undeveloped, facilitating a better formation of connections with other mycelium-binding layers.

The samples for the compression tests will be 20 x 24 x 20mm in size, as the mould can be reused for the samples to grow in. The same approach will be taken for the bending samples, with dimensions of 100 x 20 x 15mm (see paragraph 4.5.1).

Problems

1. Three out of four moulds used for the bending samples experienced deformation as a result of their exposure to the dishwasher. This was an unwise decision. Consequently, multiple different moulds were used to ensure that only those that were still in an acceptable condition were selected.

2. Thought about not needing the compression tests, but appeared to still be nessesary according to Fred Veer, becasue the jute layer should have impact on the compression tests, so those samples were made one day later than the bending samples.

Practical standpoint

Time efficiency

Less steps: simplified process

Better connections between the layers

Layering order variant 1: Mycelium

6. Mycelium layer (*Ganodema luc.*)
5. Jute
4. Mycelium layer (*Ganoderma luc.*)
3. Formwork (Sawdust + *Gan. lucidum*)
2. Mycelium layer (*Ganoderma luc.*)
1. Jute

Layering order variant 2: MBC

6. MBC (Sawdust + *Ganodema luc.)*
5. Jute
4. Mycelium layer (*Ganoderma luc.*)
3. Formwork (Sawdust + *Gan. lucidum*)
2. Mycelium layer (*Ganoderma luc.*)
1. Jute

5.3.2 Growing process

From day 5 of the experiment, visible mycelial growth was observed in both the 3p-bending samples and the compression samples. After 8 days, the compression samples had fully grown, showing a few signs of mushroom growth, and the same occurred with the 3p-bending samples after 10 days.These mushrooms were then removed by hand to be prepared for removal from the mould and to undergo a drying process for a period of 2 days. Following this, the samples were baked at a temperature of 50°C for a period of 4 hours.

		Layer 6 material	Size [b x l x h]	Temperature [°C]	Humidity level [%]	Light influence	Duration	Pressed?	Weight per piece day 1	Weight per piece last day	Density ρ [kg/m3]
Bending	1	**MBC** (Mycelium Based Composite)	3x 100x20x15 mm	20,9 - 26,4	40 - 53	Artificial light	10 days	Hand-pressed before growing process	111 g / 8 = **13,875 g per sample**	105 g / 8 = **13,125 g per sample**	437,5
	2.1	**Mycelium** (*Ganoderma lucidum*)	+3 100x20x15 mm	20,9 - 26,4	40 - 53	Artificial light	10 days	Hand-pressed before growing process	56 g / 4 = **14 g per sample**	52 g / 4 = **13 g per sample**	433,33
	2.2	**Mycelium** (*Ganoderma lucidum*)	2+2 100x20x15 mm	20,9 - 26,4	40 - 53	Artificial light	10 days	Hand-pressed before growing process	55 g / 4 = **13,75 g per sample**	52 g / 4 = **13 g per sample**	433,33
Compression	1	**MBC** (Mycelium Based Composite)	3x 20 x 24 x 20 mm	20,9 - 26,4	40 - 53	Artificial light	9 days	Hand-pressed before growing process	37 g / 8 = **4,625 g per sample**	34 g / 8 = **8,5 g per sample**	885,41
	2	**Mycelium** (*Ganoderma lucidum*)	8x 20 x 24 x 20 mm	20,9 - 26,4	40 - 53	Artificial light	9 days	Hand-pressed before growing process	38 g / 8 = **4,75 g per sample**	34 g / 8 = **8,5 g per sample**	885,41

Figure 39. Framework for mechanical strength samples prototype, own work

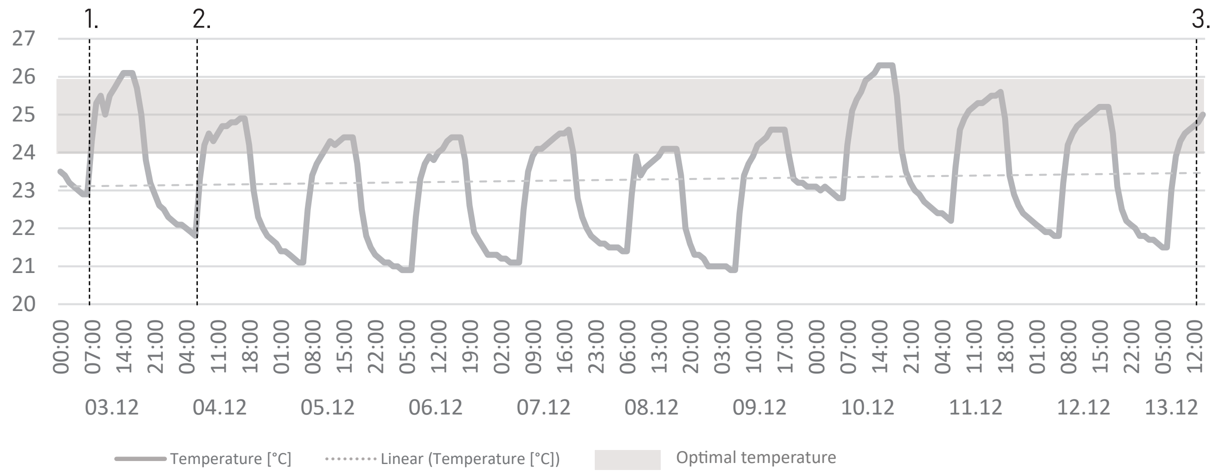


Figure 40. Temperature diagram during experiment 7 (Based on information provided from the app 'AranetHome', own work)

5.3.3 Temperature diagram

1. Bending samples are places within the hotbox.
2. Compression samples are places within the hotbox.
3. All samples taken out of the hotbox: Lights turned off.

5.3.4 Optimal growing process

Following a series of seven experiments on the subject of mycelium growth and testing, the present moment is opportune for the purpose of providing a conclusion to the following question: *'What is the most optimal process for the cultivation of mycelium-based composites?'*

1. Substrate preparation
The selection of a fibrous, nutrient-rich substrate with proven compatibility for strong composite formation is of fundamental importance. Sawdust and other agricultural by-products, such as plant fibres, can be ideal options for achieving high density and compressive strength. Subsequent to substrate selection, it is essential to thoroughly sterilise the substrate, tools, and surfaces to prevent contamination during the growth phase. Recommended methods for sterilisation include boiling or autoclaving.

2. Inoculation
A pre-cultivated mycelium inoculant, such as grain spawn or Hedelcomposite, should be mixed with the prepared substrate. It is essential to ensure an optimal ratio of inoculant (10-20% of the total volume) to promote uniform growth. Approximately 10% of the total weight should be added in the form of flour, in order to provide the mycelium with a stimulant and to ensure greater homogeneity of the sample. The substrate's moisture content should be carefully adjusted to create an optimal growing environment, ensuring neither dryness or overexposure to moisture.

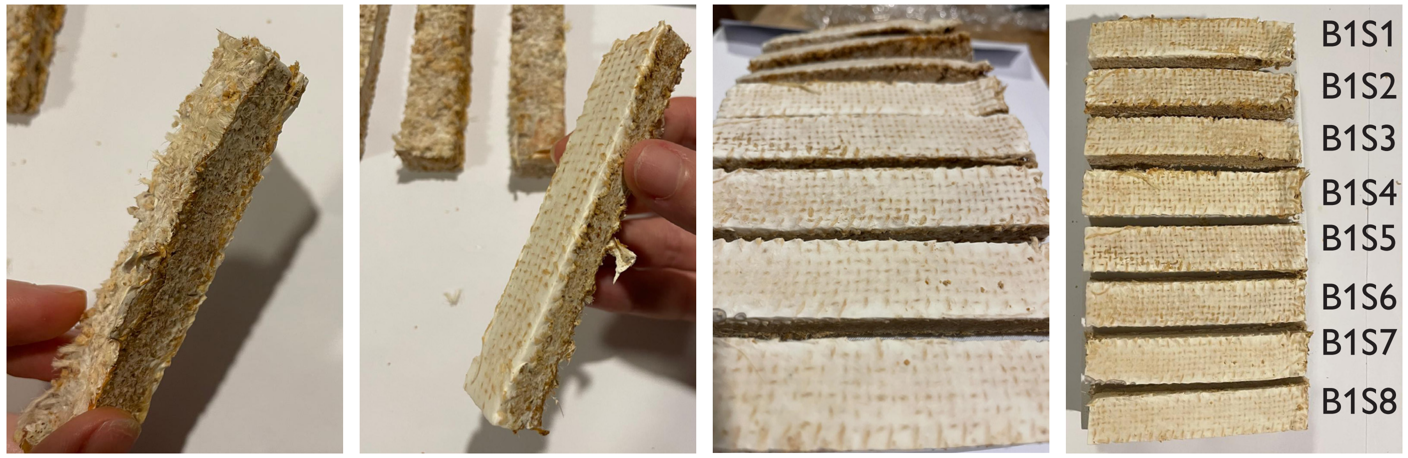
3. Packing into moulds
Use breathable moulds that allow oxygen to reach the material, ensuring consistent growth. Prior to use, it is essential to sterilise the moulds to ensure the absence of contaminants. In the context of layering, a strategic approach is crucial for enhancing structural stability. The combination of the mycelium-based composite with additional reinforcing organic materials , like jute or cotton, during the layering process results in the formation of a stronger composite structure.

4. Growth phase
It is recommended to maintain a controlled environment with a temperature range of 24–26°C and relative humidity levels of 80–90%. These conditions are conducive to the rapid and consistent colonization process. The growth duration is of significance in this process; it is necessary to allow the growth to progress within the mould for approximately 5–7 days to ensure the substrate fibres are fully bound. If required, the growth can be extended outside the mould to strengthen the outer layers.

5. Drying and post-treatment
The process of stopping mycelial growth can be achieved through the application of heat to the material. The duration and temperature of this process are dependent on the desired behaviour of the sample. The material can be subjected to a heating process at room temperature, with a range of 70°C for a duration of 5 hours to 2 days. This procedure is effective in removing residual moisture, stabilising the material's structure, and ensuring its durability. The application of eco-friendly, bio-based coatings can be employed afterwards to enhance the material's resistance to moisture or to improve its surface performance.

5.3.4 Labeling

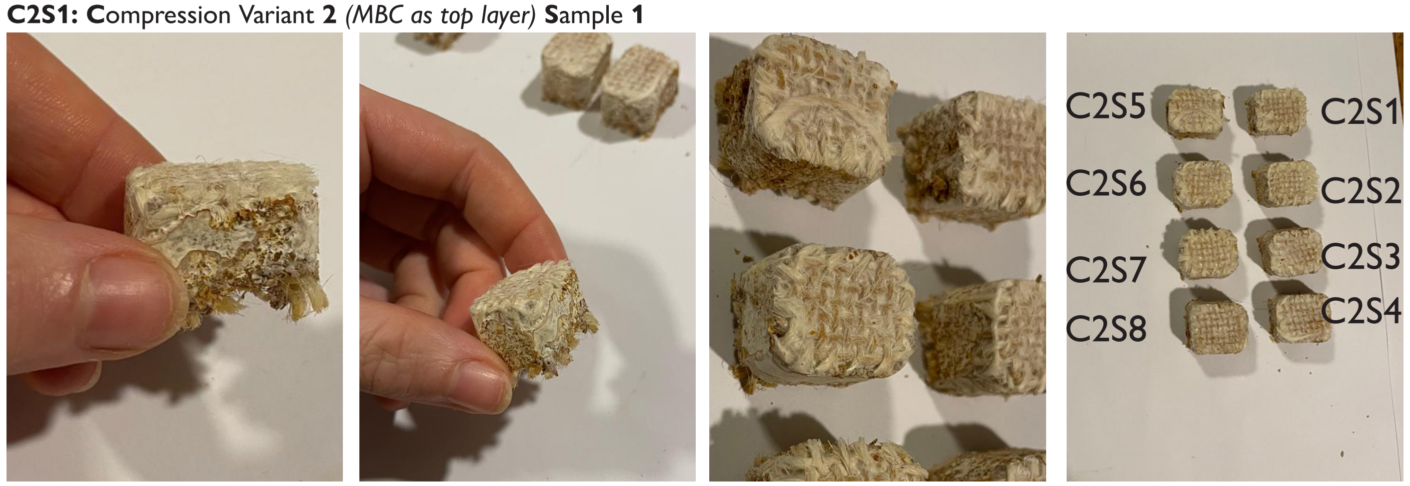
B1S1: Bending Variant **1** *(Mycelium as top layer)* **S**ample **1**



B2S1: Bending Variant **2** *(MBC as top layer)* **S**ample **1**

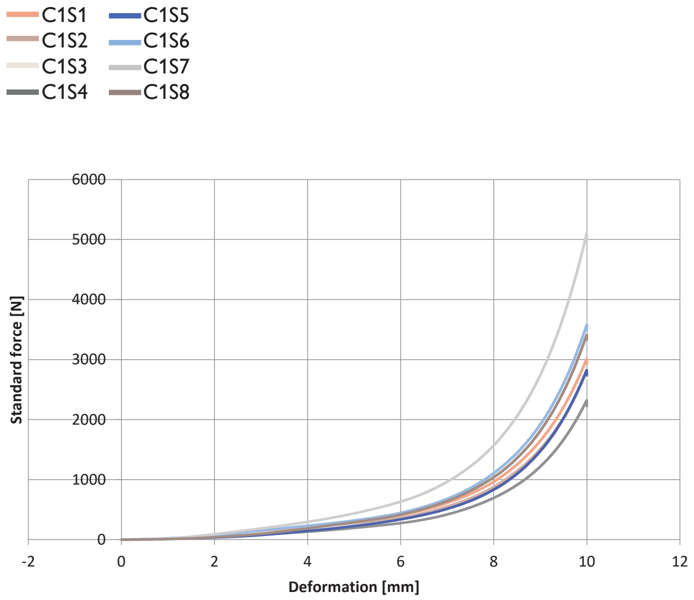
C1S1: Compression Variant **1** *(Mycelium as top layer)* **S**ample **1**

C2S1: Compression Variant **2** *(MBC as top layer)* **S**ample **1**

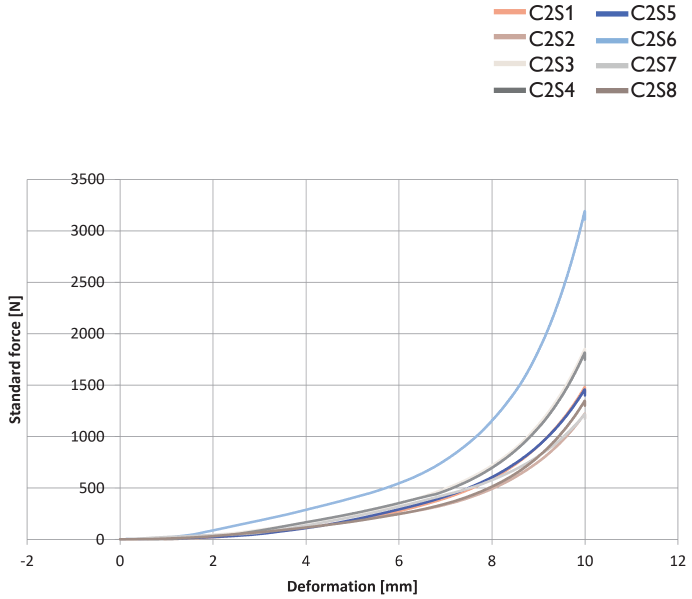


5.3.4 Compression

Variant 1: Mycelium top layer



Variant 2: MBC top layer



Calculations stiffness (Young's modulus / Elastic modulus E)

See 4.5.4 Compression tests p. 71 for the formulas

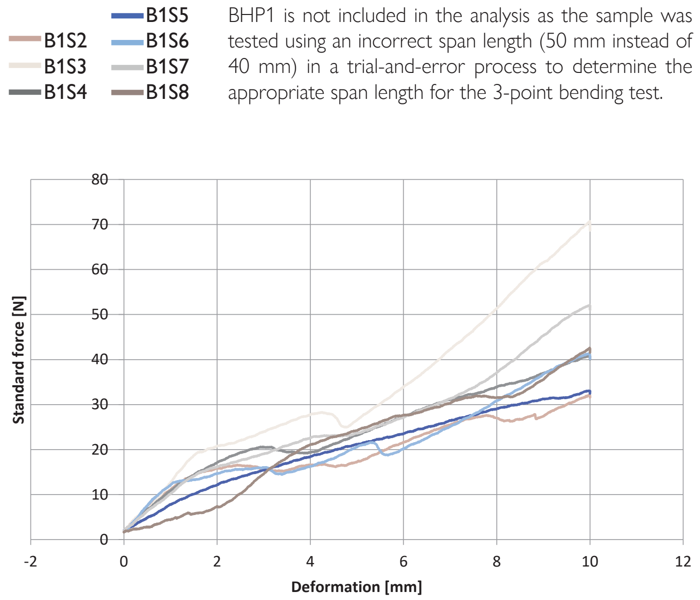
Sample number	F2 [N]	F2 / A [N/mm2]	F4 [N]	F4 / A [N/mm2]	σ [MPa]	E [MPa]	Mean E [MPa]
C1S1	70,29	1,46	203,82	4,25	2,78	27,82	
C1S2	50,73	1,06	176,55	3,68	2,62	26,21	
C1S3	51,05	1,06	163,42	3,40	2,34	23,41	
C1S4	44,73	0,93	132,28	2,76	1,82	18,24	
C1S5	33,89	0,71	143,92	3,00	2,29	22,92	
C1S6	71,81	1,50	230,63	4,80	3,31	33,09	
C1S7	90,26	1,88	294,68	6,14	4,26	42,59	
C1S8	38,17	0,80	187,16	3,90	3,10	31,04	28,17
C2S1	21,24	0,44	112,43	2,34	1,90	19,00	
C2S2	31,44	0,65	117,96	2,46	1,80	18,03	
C2S3	45,78	0,95	163,78	3,41	2,46	24,58	
C2S4	28,72	0,60	167,35	3,49	2,89	28,88	
C2S5	23,24	0,48	111,01	2,31	1,83	18,29	
C2S6	88,20	1,84	288,67	6,01	4,18	41,76	
C2S7	41,69	0,87	136,51	2,84	1,98	19,76	
C2S8	32,20	0,67	116,54	2,43	1,76	17,57	23,48

Figure 41. Calculation-table Young's Modulus prototype samples, own work

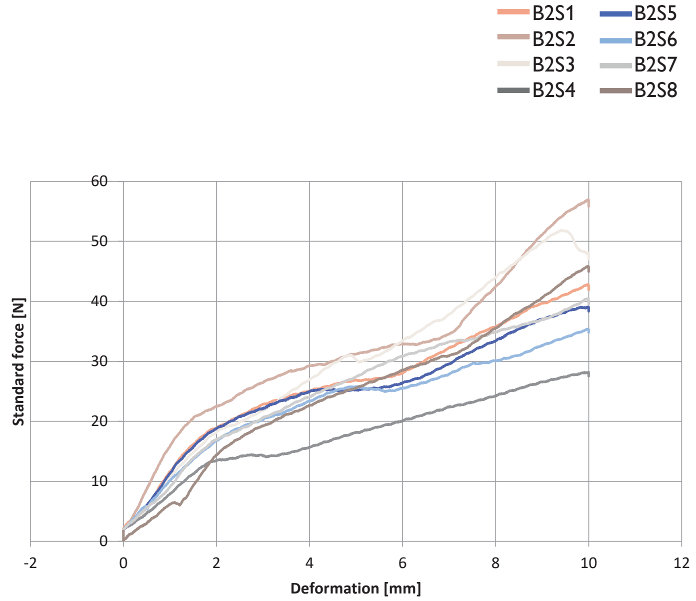
5.3.5 Three-point bending tests

Variant 1: Mycelium top layer

BHP1 is not included in the analysis as the sample was tested using an incorrect span length (50 mm instead of 40 mm) in a trial-and-error process to determine the appropriate span length for the 3-point bending test.



Variant 2: MBC top layer



Calculations bending tests maximum stress and standard deviation

See 4.5.5 Three-point bending tests p. 74 for the formulas

	Variant 1: Mycelium as top layer					Variant 2: MBC as top layer				
Sample number	Maximum strength [N]	Standard Deviation [N]	Maximum moment [Nmm]	Maximum stress σ [MPa]	Standard Deviation [MPa]	Maximum strength [N]	Standard Deviation [N]	Maximum moment [Nmm]	Maximum stress σ [MPa]	Standard Deviation [MPa]
1	-	-	-	-	-	42,80	0,22	428,05	0,57	0
2	32,23	12,46	322,34	0,43	0,17	57,00	14,42	569,99	0,76	0,19
3	70,72	26,03	707,22	0,94	0,34	51,87	9,29	518,69	0,69	0,12
4	40,84	3,85	408,41	0,54	0,06	28,19	14,39	281,92	0,38	0,19
5	33,07	11,62	330,69	0,44	0,16	39,07	3,51	390,68	0,52	0,05
6	41,30	3,39	412,96	0,55	0,05	35,39	7,19	353,86	0,47	0,10
7	52,09	7,40	520,91	0,69	0,09	40,47	2,11	404,71	0,54	0,03
8	42,60	2,09	426,02	0,57	0,03	45,84	3,26	458,39	0,61	0,04
Mean	44,69	9,55	446,94	0,60	0,13	42,58	6,80	425,78	0,57	0,09

Figure 42. Calculation-table Maximum stress prototype samples, own work

5.3.6 Comparison & conclusions

In comparison with the outcomes observed in the absence of the jute layer, which was employed to enhance tensile strength, the tests involving both compression and tension with the incorporated jute layers as sandwich panels demonstrated significantly superior results.

Compression tests:
It is evident from the graph of the samples with jute during the compression tests that the initial slope is subtle, with a progressive increase in steepness. At the point where the slope becomes maximal, deformation has already occurred. It is evident from the graph of the samples with jute during the compression tests that the initial slope is subtle, with a progressive increase in steepness. At the point where the slope becomes maximal, deformation has already occurred. Consequently, the resistance of the sample increases and the force also increases significantly for the same deformation. This raises the potential for further research into compressing the MBC after it has fully grown to investigate the mechanical properties.

Young's modulus & maximum compression force

	Ganod. luc. + sawdust without jute	Variant 1 Mycelium top layer + jute	Variant 2 MBC top layer + jute
Mean E	24,94 MPa	28,17 MPa	23,48 MPa

The results demonstrate that the samples containing *Ganoderma lucidum* and sawdust have a Young's modulus that is not significantly different from the samples with added jute layers. The stiffness remains constant during compression prior to the graph becoming linear, indicating that the stiffness is similar before permanent deformation occurs. However, the maximum force applied for the same 8 mm deformation is significantly higher in the samples with jute than in the samples without jute. Specifically, the maximum force applied for an 8 mm deformation was recorded as **591,00 N** (paragraph 4.5.4) for the samples without jute and **1570,47 N** (paragraph 5.3.4) for the sandwich panel samples, including the jute layers.

3-point bending tests
The samples reinforced with jute demonstrated significantly improved outcomes in the three-point bending tests. The additional layers of jute provided the samples with enhanced tensile strength, thereby reducing their breakage point and increasing their resistance to deformation.

As demonstrated in the underlying table, the maximum force applied is significantly higher in the jute samples. Furthermore, the maximum moment and maximum stress are also higher in these samples. The jute layer provides more consistent results, which makes them more applicable for practical use.

V1: Jute + Sawdust + *Ganoderma lucidum*


Strongest combination, but not comparable to construction materials


More even results in testing

	Maximum strength [N]	Standard Deviation [N]	Maximum moment [Nmm]	Maximum stress [MPa]	Standard Deviation [MPa]
Sawdust *Ganod. luc.* (without jute)	15,25	3,71	153,54	0,21	0,05
V1: Jute + Mycelium top layer	44,69	9,55	446,94	0,60	0,13
V2: Jute + MBC top layer	42,58	6,80	425,78	0,57	0,09

Figure 43. Table with comparison results bending tests, own work

Building materials

	Mechanical properties			Physical properties		
Material	**Compressive strength**	**Tensile Strength**	**Young's modulus**	**Density**	**Thermal conductivity**	**Source**
	[MPa]	[MPa]	[GPa]	[kg/m^3]	[W/mK]	
Concrete (insulating lightweight)	0,5 - 2,8	0,1 - 0,3	0,6 - 1,53	900 - 1,4e3	0,1 - 0,7	Granta EduPack 2023
High density concrete	30,6 - 36,6	3,1 - 3,7	40,2 - 41,6	4,9e3 - 5,5e3	1,6 - 2,5	Granta EduPack 2023
Low alloy steel, SAE 8630, cast, quenched & tempered	827 - 914	915 - 1,01e3	196 - 204	7,81e3 - 7,84e3	42 - 48	Granta EduPack 2023
Stainless steel, austentic, AMST CH-10, cast, water quenched	333 - 363	547 - 667	189 - 197	7,67e3 - 7,77e3	14 - 16	Granta EduPack 2023
Timber: oak (l, quercus spp.)	68,2 - 83,3	133 - 162	20,6 - 25,2	850 - 1,03e3	0,16 - 0,2	Granta EduPack 2023
Timber: oak (t, quercus spp.)	12,8 - 15,6	7,1 - 8,7	5 - 5.58	850 - 1,03e3	0,16 - 0,2	Granta EduPack 2023
Mycelium-based composites	0,17 - 1,1	0,03 - 0,18	0,05e-3 - 0,29e-3*	59 - 552	0,05	(Jones et al., 2020)
MBC (sawdust + *Gan. luc.*)	Not tested	Not tested	0,025	299,48 - 587,5	Not tested	Own experiments
Sandwich panel (MBC + jute)	Not tested	Not tested	0,028	433,33 - 855,41	Not tested	Own experiments

Figure 44. Comparison table, building materials own work

5.4 Design

"What is the most suitable building element for mycelium-based composites, existing of the sandwich panel composition?"

5.4.1 Complex geometry

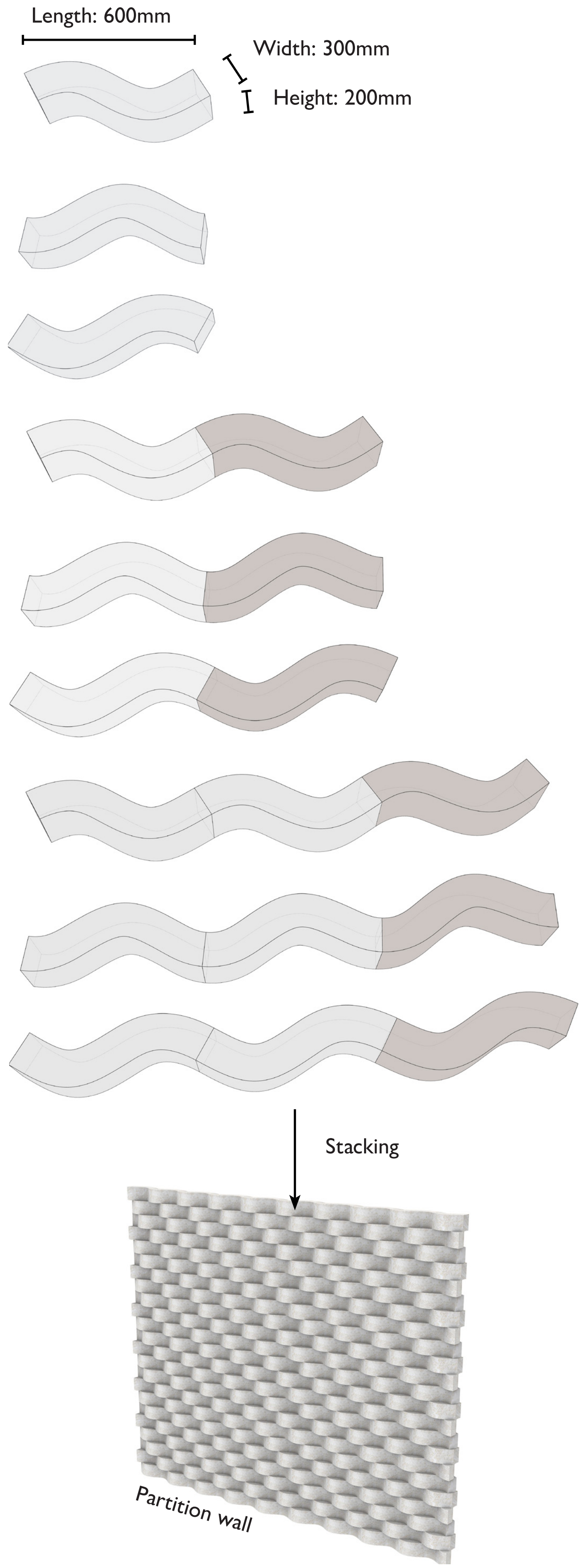
Complex shaped
In order to ensure optimal utilisation of the advantages offered by mycelium, the partition wall will be designed with a complex shape. This approach is intended to enhance both the visual appeal and the acoustic properties of the environment.

Acoustics
The term "acoustic comfort" is used to describe a building or house that has minimal intruding noise from outside and an appropriate reverberation time within the interiors. Research has demonstrated that spaces which are acoustically comfortable have the capacity to enhance productivity, happiness and the overall health of those who occupy them. (mogu.bio, 2024)

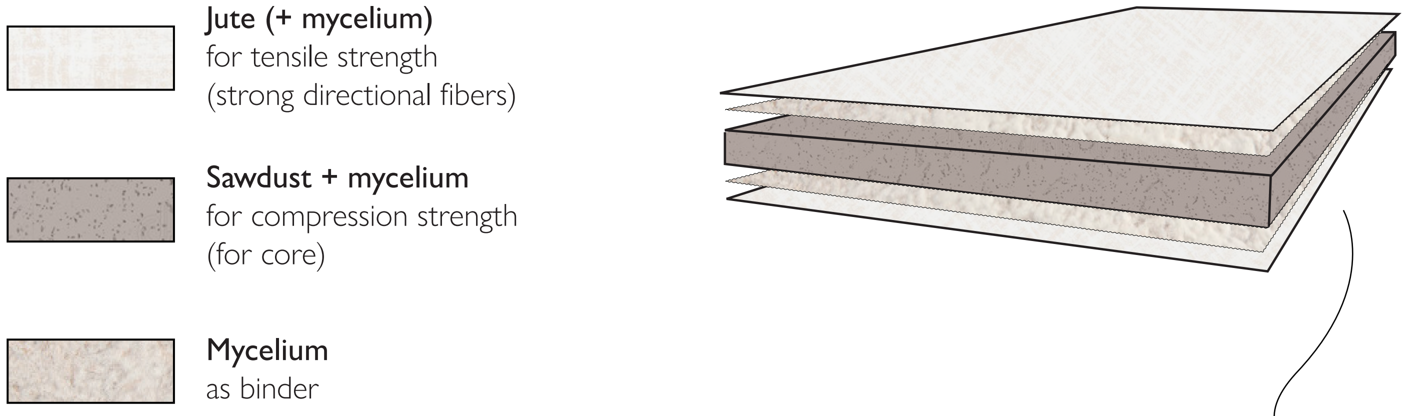
Corrugated blocks
The corrugated sandwich wall has been selected for its potential to offer a range of design options, with three different designs for the blocks, thereby facilitating the creation of a variety of interesting combinations for partition walls. The corrugated shape is efficient in structural strength and stiffness by distributing loads more effectively, it is efficient in acoustic insulation, because the waves inherently contribute to sound absorption, the geometry of the waves helps to scatter and diffuse sound waves, reducing echoes and reverberation. This design is also more aesthetic versatile, since the corrugated design can serve as an aesthetic element, offering a modern and dynamic appearance.

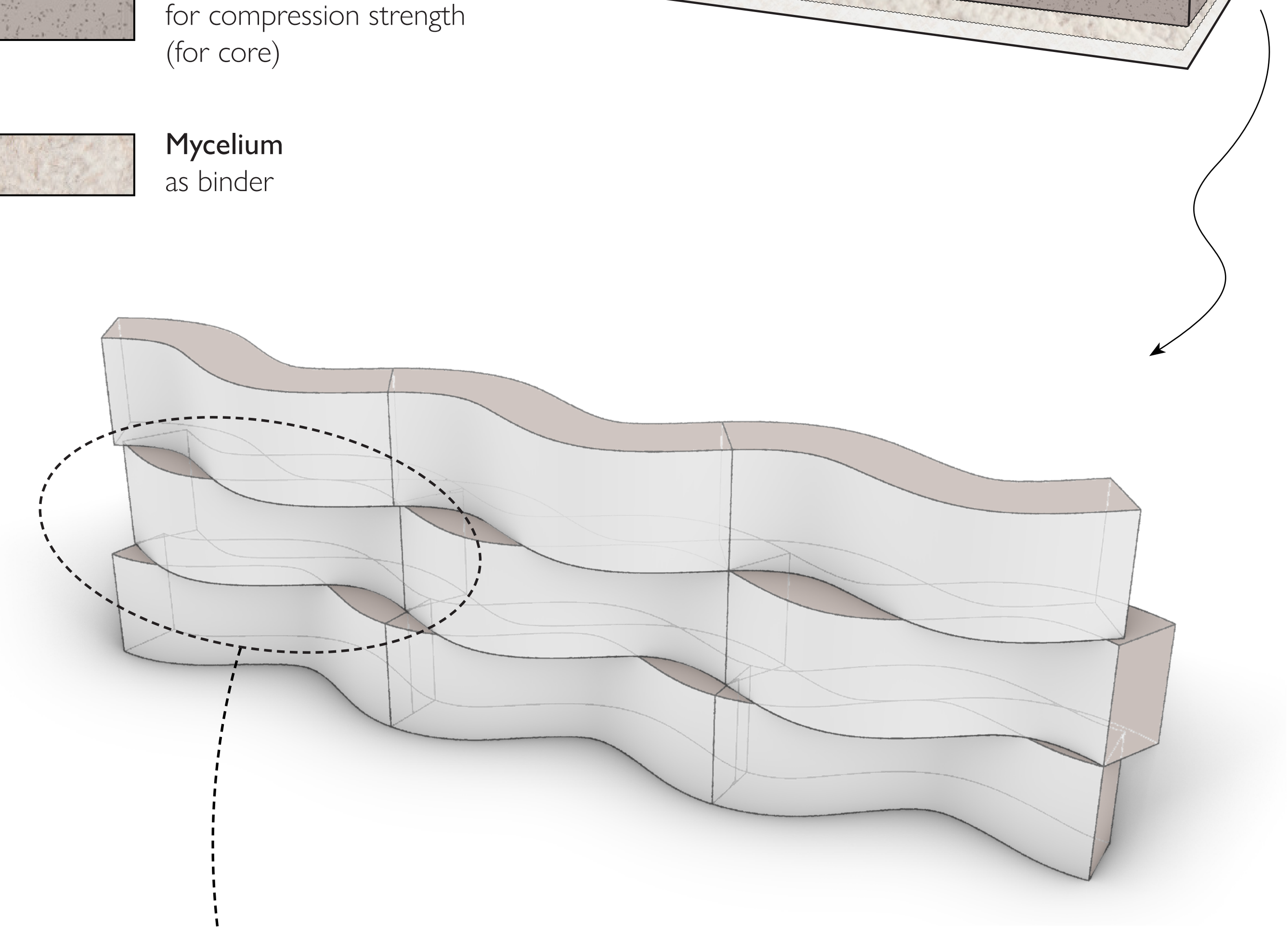
5.4.2 Reusable moulds

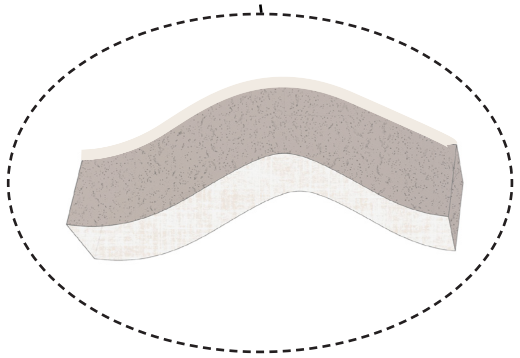
The blocks have been designed to facilitate the repeated use of the same mould in order to construct a single layer of the partition wall.



Layering to suit the unique properties of mycelium







Corrugated blocks:

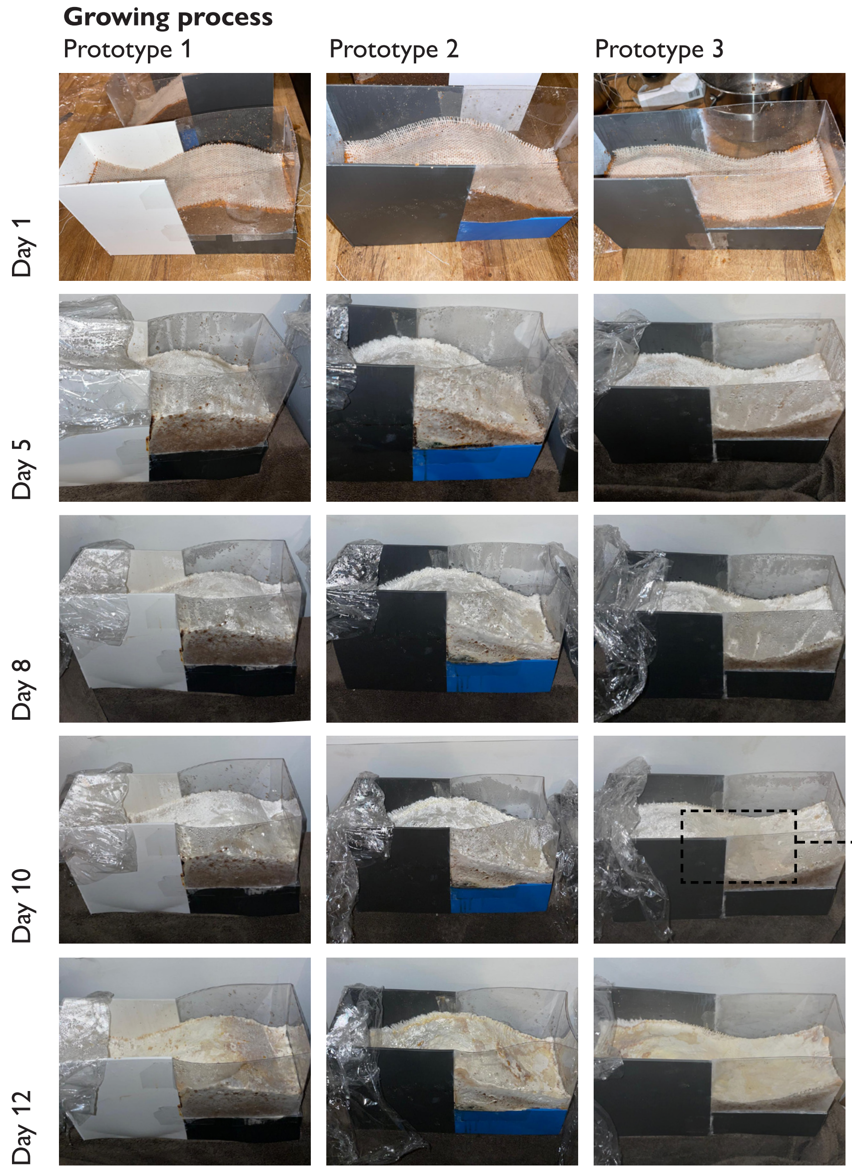
- Efficient in structural strength and stiffness;
- Efficient in acoustic insulation and reverberation time;
- Aesthetic versatility.

5.4.3 Growing process

Scale

The final prototype consists of three blocks, scaled at a rate of 1:2, due to the fact that otherwise there would be insufficient space for them to fit into the oven. In addition, in order to save material and demonstrate the same potential as the 1:1-scaled model, it was decided to scale the prototype at 1:2.

The three different prototype variants will be developed into three separate moulds, with the moulds themselves being partially 3D printed to achieve the desired corrected shape. These moulds can be reused to produce the remaining partition wall blocks.



Gel development

At day 10, all three variants exhibited signs of gel formation in the lowest points of the blocks. This phenomenon is likely to have occurred due to excessive moisture accumulation in these areas. To ascertain the potential for further mycelial development, the gel is extracted from the samples.

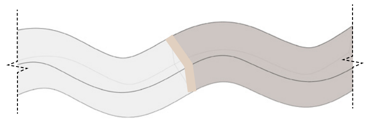
It is important to note that, due to the unavailability of the hotbox during the Christmas holidays, no temperature diagram is available for this growing process, which was therefore conducted from home above the radiator, which was set at 24°C during the day.

	Size [b x l x h]	Temperature [°C]	Humidity level [%]	Light influence	Duration	Pressed?	Weight day 1	Weight per piece last day	Density ρ [kg/m3]
V1	100 x 300 x 150 mm	18 - 28	Unknown	Natural light	12 days	Hand-pressed before growing process	5203 g	1879 g	417,55
V2	100 x 300 x 150 mm	18 - 28	Unknown	Natural light	12 days	Hand-pressed before growing process	5449 g	2013 g	447,33
V3	100 x 300 x 150 mm	18 - 28	Unknown	Natural light	12 days	Hand-pressed before growing process	4983 g	1724 g	383,11

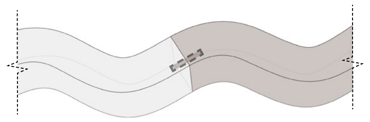
Figure 45. Framework for final prototype variants, own work

5.4.3 Connection between blocks

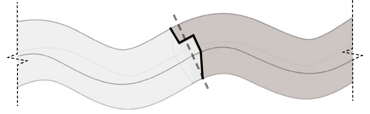
In the context of the connection between different blocks, a wide range of options is available. However, in order to maintain the bio-based quality of the block, the following options appears to be the most suitable:



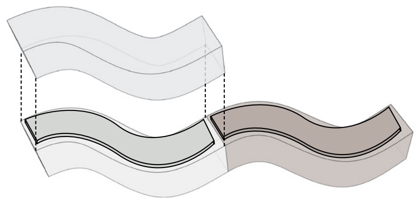
Mycelium as glue, when the blocks are not fully grown and baked yet;



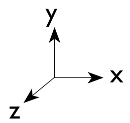
Wooden pinns (for all directions)



A minor change in the design of the block with a built-in click system in the z-direction (with eventually an added wooden pinn)



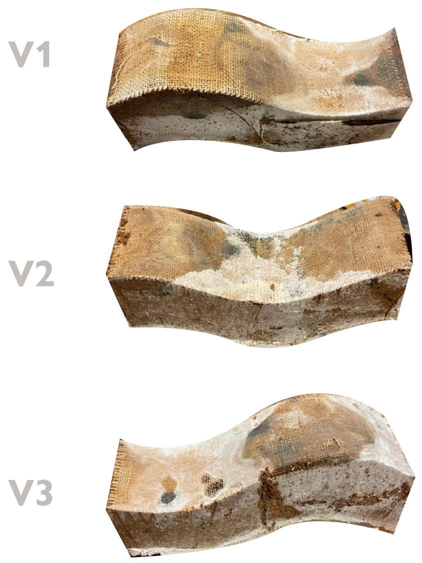
A minor change in the design of the block with built-in click system in the x- and z-direction



5.4.4 Drying process

Following a period of 12 days, the three variants have reached a sufficient stage of development to be removed from their moulds. The darker areas visible in the images below are indicative of residual moisture.

Following a drying process lasting two days, the blocks will have a white skin, which is both aesthetically appealing and improves the strength of the entire block.The blocks will then be baked at 50 degrees for five hours (a duration slightly longer than that applied to the other samples, due to their increased size). Thereafter, they will be ready for their intended application in the partition wall.



5.4.5 Conclusion

This chapter demonstrates the feasibility of designing and manufacturing mycelium-based composites (MBCs) for use in complex geometry building blocks for internal partitions.The study explores the material's unique properties, emphasising sustainability, biodegradability, and its potential as a bio-based alternative for building elements.

The process involved careful experimentation with substrates, fungal species, and added layers to optimize material properties and growth consistency. A key aspect of the manufacturing process involved testing the composition and layering configurations to enhance the material's functional performance. Among the configurations tested, the most effective for acoustic performance was a layered structure consisting of jute on the outer surfaces, MBC as the central core, and mycelium acting as the binder. This configuration achieved a balance between structural stability and enhanced acoustic insulation, making it an ideal candidate for internal partition applications.

The moulds used for the prototypes were complex geometries, and the results showed that the mycelium can adapt to these shapes while maintaining its material integrity.Post-processing steps, such as controlled drying and heat treatment, enhanced the durability and dimensional stability of the composites.The findings confirm that MBCs can be engineered to meet both functional and aesthetic requirements, offering lightweight, sound-insulating, and environmentally friendly solutions.

Despite their limited mechanical strength when compared to traditional materials, the lightweight structure, with added tensile strength, and acoustic properties (according to Mogu.bi0, 2024) of MBCs render them highly suitable for non-load-bearing applications.

Figure 46. Render waste management building Voorhout, provided by Witteveen+Bos, 2024

Figure 47. Render meeting room waste management building Voorhout, including MBC partition wall, own work

5.4.6 Waste management building in Voorhout

In order to demonstrate the true potential of mycelium-based composites and the manufactured blocks, reference is made to a model provided by Witteveen+Bos. This project has not yet been realised; however, it is an office for waste management that has been constructed with a secondary steel construction and a fully bio-based facade. Due to its sustainable nature, it was an ideal location for the partition wall.

The partition selected for the rendering is situated between the cafeteria and a meeting room, necessitating sound-absorbing properties and a reduced reverberation time. The targeted reverberation period for this particular wall was set at 0.6 seconds. The absorption level of a composite comprising sawdust, *Ganoderma lucidum* and jute was not the focus of this particular research; however, as illustrated in Figure 19 on page 22, the mycelium-based composite utilised in the Mogu acoustic panels exhibits optimal properties for this application, even when the panels are thinner than the initial prototype blocks. This is due to the fact that the most common sound in such a setting would be human conversation, which occurs within the range of 250-1000 Hz. This frequency range is well-suited to mycelium-based composites (Mogu.bio, 2024).

06
Conclusion & Discussion

06 Conclusion & Discussion

6.1 Conclusion

This thesis explored the potential of mycelium-based composites as an innovative building element for internal applications. The research focused on a material-driven approach to identify possible building applications.

6.1.1 Experimentation and findings

Based on the literature outcome, a number of substrates were selected for testing in order to assess their rate of growth for the fungal cultivation, as well as their mechanical strength and formability. The results of the substrate testing phase indicated that **hemp, sawdust, cotton, and jute** were the most effective. These selected substrates provided suitable conditions for fungal growth.

In the case of the fungi, based on the findings of the literature review the decision was taken to initially test *Pleurotus ostreatus*. Subsequently, *Ganoderma lucidum* was added to the upcoming experiments based on the findings of expert interviews. In the comparison of fungal species, no single species demonstrated characteristics in terms of the growing process that were considered to be superior to the other. Both *Pleurotus ostreatus* and *Ganoderma lucidum* demonstrated favourable growth and bonding characteristics, although their performance was influenced by the substrate employed. Consequently, all possible combinations of fungal species with sawdust and hemp were subjected to mechanical strength testing.

The results of the mechanical tests presented a certain degree of mixed results and inconsistency. While sawdust combined with *Ganoderma lucidum* exhibited the highest force resistance during compression tests, the bending tests demonstrated a relative high degree of divergence, indicating variation in the composite's distribution. These findings emphasise **the necessity for an optimal distribution** within the samples, which can be achieved through thorough mixing of the various materials during the preparation phase.

This level of consistency was achieved with the next tests on the prototype samples, as evidenced by the more uniform results and graphs, making these samples more reproducible.

6.1.2 Prototype Development

Due to the best outcome during mechanical testing test, the development of the prototype focused on using sawdust combined with *Ganoderma lucidum* as the substrate-fungal combination for the blocks core material. To enhance tensile strength, jute layers were incorporated into the outer skin on the block, relateble to the structure of a sandwich panel, where the outer layer provides tensile strength.

A key innovation of the prototype lies in **the role of mycelium as the glue that binds the different layers together**. It is essential that each individual layer is formed from a sterilised substrate that the mycelium can feed and grow on. In contrast to blocks made out of traditional building materials that depend on synthetic adhesives, mycelium serves as a bio-based binder, making it the main material of the block. This **single-material approach** not only simplifies the production process but also aligns with the principles of a circular economy by using waste streams and offering complete biodegradability.

6.1.3 Main Research Question

The primary objective of this thesis was to adress the main research question:

> *"How can **mycelium-based composites** be engineered and optimized for use as a **building element** in **internal applications**?"*

The conducted research demonstrates that mycelium-based composites can be engineered and optimised for use as an innovative building element in internal applications through the careful selection of substrates, fungal species and fabrication methods. The study demonstrates the potential of mycelium as both a binder and a primary material for lightweight, sustainable, and circular building materials. The principal findings are:

1. Optimisation of the material
The selection of suitable substrates and fungal species is of critical importance in determining the mechanical properties of the composite. The combination of sawdust with Ganoderma lucidum resulted in the optimal outcomes for compressive strength, while the incorporation of jute layers exhibited the maximum tensile strength. The selection of the strongest combination of materials is made in this manner to minimise the material requirement for the same component strength. This is beneficial in terms of material optimisation and the minimisation of spatial demands in the design. The sandwich panel structure serves to illustrate the potential of employing mycelium-based composites in circular and innovative internal building elements.

2. Mycelium as a binder and main material
Mycelium acts as the bio-based glue that binds the composite together, providing cohesion without synthetic adhesives. This innovative use of mycelium simplifies the material composition, reduces reliance on multi-material systems, and enhances sustainability.

It is evident that the prototype offers a promising indication of the potential of mycelium-based composites. However, challenges still exist in achieving consistency in mechanical properties. The utilisation of agricultural waste streams and the circular nature of mycelium indicate that it is a promising innovation for the sustainable building industry. This research provides a foundation for integrating mycelium-based composites into the built environment.

6.2 Discussion

This graduation project initially tried to explore how mycelium-based composites could be engineered for use as self-supporting structures in construction. However, as the research progressed, it became clear that while mycelium-based composites are innovative and sustainable, they lack the mechanical strength required for traditional load-bearing applications. This insight resulted in a shift in approach that was fundamental to the project, **moving away from an application-driven focus and towards a material-driven one.** Rather than forcing the material into an unsuitable application, the research underwent a shift in focus towards an understanding of the properties of mycelium-based composites, with the objective of identifying the areas in which their unique qualities could be most effectively utilised.

6.2.1 Challenges, limitations and research gaps

The experimental phase presented a number of significant challenges and potential research gaps that had an impact on the progress and outcomes of the research:

1. Sterilisation issues
It was crucial to ensure effective sterilisation in order to facilitate optimal mycelium growth; however, this proved to be a challenge. When substrates or tools were not thoroughly sterilized, other microorganisms or bacteria competed with the mycelium, thereby inhibiting its growthand developing external mould. Furthermore, the use of boiling water for the sterilisation of plastic moulds resulted in deformation, making them unsuitable for use. This highlighted the necessity for a fine balance to be reached in order to achieve optimal growth conditions, as well as the practical difficulties inherent in working with bio-based materials.

2. Moisture dependency
The lack of necessary moisture in the substrate resulted in the absence of mycelial growth, as fungi require a moist environment to achieve optimal growth and development. This highlighted the necessity for precise control over the preparation of the substrate, as even minor differences could have a significant impact on the growth process. An analysis of the precise ratio of moisture in the substrate for the mycelium to grow on is a valuable future area of investigation. Additionally, precisely testing the ratio of mycelium-based composite (MBC) to flour would be beneficial for optimisation of fungal growth.

3. Inconsistent mould development
Some samples showed unexpected mould growth that could not be explained by the identical preparation environments. This demonstrated the unpredictable nature of biological materials and indicated a need for further research to gain a deeper understanding of the environmental and experimental factors influencing external mould growth. However, this inconsistency also highlights the unique potential for adaptability in biological materials, offering opportunities to explore innovative solutions for controlling and optimizing growth conditions. With further research and a more clean environment, these challenges could lead to significant breakthroughs in understanding and improving the predictability of mycelium-based composites, thereby enhancing their potential for builidng applications.

4. Living material challenges
One of the most defining aspects of mycelium is that it is living and responsive, which sometimes led to unpredictable outcomes. In one example, the mycelium grew within 15 days, while in another experiment with the same material combination and almost the same environmental regulations, the sample was almost fully grown in four days. The behaviour of mycelium can be unpredictable and inconsistent, which presents a challenge in controlling the process. However, this living nature also offers an opportunity for for adaptive and innovative solutions, like the ability to heal itself, making the material highly adaptable but difficult to standardise.

5. Challenges with prototype shape and design
The creation of a complex prototype that fully utilises the formability advantage of mycelium proved to be a personal challenge. The utilisation of Grasshopper for design, a tool I was less familiar with, resulted in a significant investment of time for learning and troubleshooting, which consequently delayed progress. The necessity for a complex shape was in my eyes fundamental to demonstrate mycelium's capability to grow in any complex shape, thereby introducing an additional layer of difficulty to the process. More time would have allowed for further exploration of different design posibilities, experimentation with combinations of various types of mycelium and substrates to optimize properties in a single panel or block, and testing various pressing techniques during or after the growth process. Additionally, further investigation into mycelium's self-healing capabilities could have enriched the project.

6. Timing of expert input
The timing of expert input was occasionally insufficient to influence experiments that had already started, which limited the scope for incorporating their insights into the research and experiments. Consequently, this resulted in the necessity for additional experiments or the realisation that some experiments were not meant to succeed due to factors such as the lack of moisture. While this was certainly not a reflection on the experts themselves or their expertise, it was nevertheless an inconvenient and unavoidable aspect of the research process.

7. End of life
An additional area of investigation that I intended to pursue, but was limited by time constraints and the scope of the research, is a comprehensive analysis of the life cycle of mycelium, including accelerated aging tests and strategies to extend its lifespan.

A critical area for further investigation involves understanding the final stages of mycelium's life cycle. It is important to determine whether the material becomes brittle and prone to breaking over time or if ambient humidity gradually compromises its structural integrity. Additionally, examining the processes at the end of the composting cycle could provide valuable insights. At what stage does the compost transition into a viable substrate for plant growth, and when does it become a new mycelium formation? While this largely depends on the composition of the mixture, the exact mechanisms remain unclear. Could increasing the mycelium content enhance the compost's suitability for fostering new growth? Identifying the optimal ratio for this process would be essential for maximizing the material's sustainability and regenerative potential.

6.2.2 Shift in approach

The change in approach, from driven by applications to driven by materials, enabled a more nuanced examination of the characteristics and potential of mycelium composites. Rather than attempting to impose a structural application on a material that was not fully suited to it, the research focused on identifying the areas where the mycelium's strengths, including biodegradability, lightweight nature and formability, could be most effectively utilised. This shift in approach has led to new insights into the material's capabilities, which could inform future projects that use mycelium for non-load-bearing applications such as insulation, acoustic panels or modular design elements.

6.2.3 Reflections and future directions

Despite the limitations and the natural unpredictability of mycelium, it is important to acknowledge its numerous advantages, including its broad versatility. This research has laid a strong foundation for understanding and working with mycelium-based composites. While I had hoped to investigate further, including:

- Combining different types of mycelium and substrates for optimal results;
- Investigating more about the advantage of mycelium to heal itself;
- Gain a deeper understanding of the ratio of moisture to substrate required for mycelial growth;
- Identify the precise cause of external mould development during the growth process;
- Do more research about the pressing techniques during and after the growing process;
- Analyse more about the end of life stages,

the findings still provide a significant step toward integrating mycelium-based composites into sustainable building practices. This study contributes to the broader conversation about eco-friendly materials, emphasizing the importance of adapting material-driven approaches **to suit the unique properties** of bio-based innovations.

07
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07 Bibliography

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7.2 Figure references

1. Methodology, own work

2. Time Schedule, own work

3. Mycelium, own work

4. Growing process mycelium, Based on Vanden Elsacker & Vrije Universiteit Brussel, 2021, own work

5. Different stages of the growing process with the used tools, BlueCity, own photo

6. Different post-processing options for different sample behaviour (Based on interview and lab tour with Mrinal Chaudhury, Appendix 8.1.6, own work)

7. Advantages of mycelium, own work

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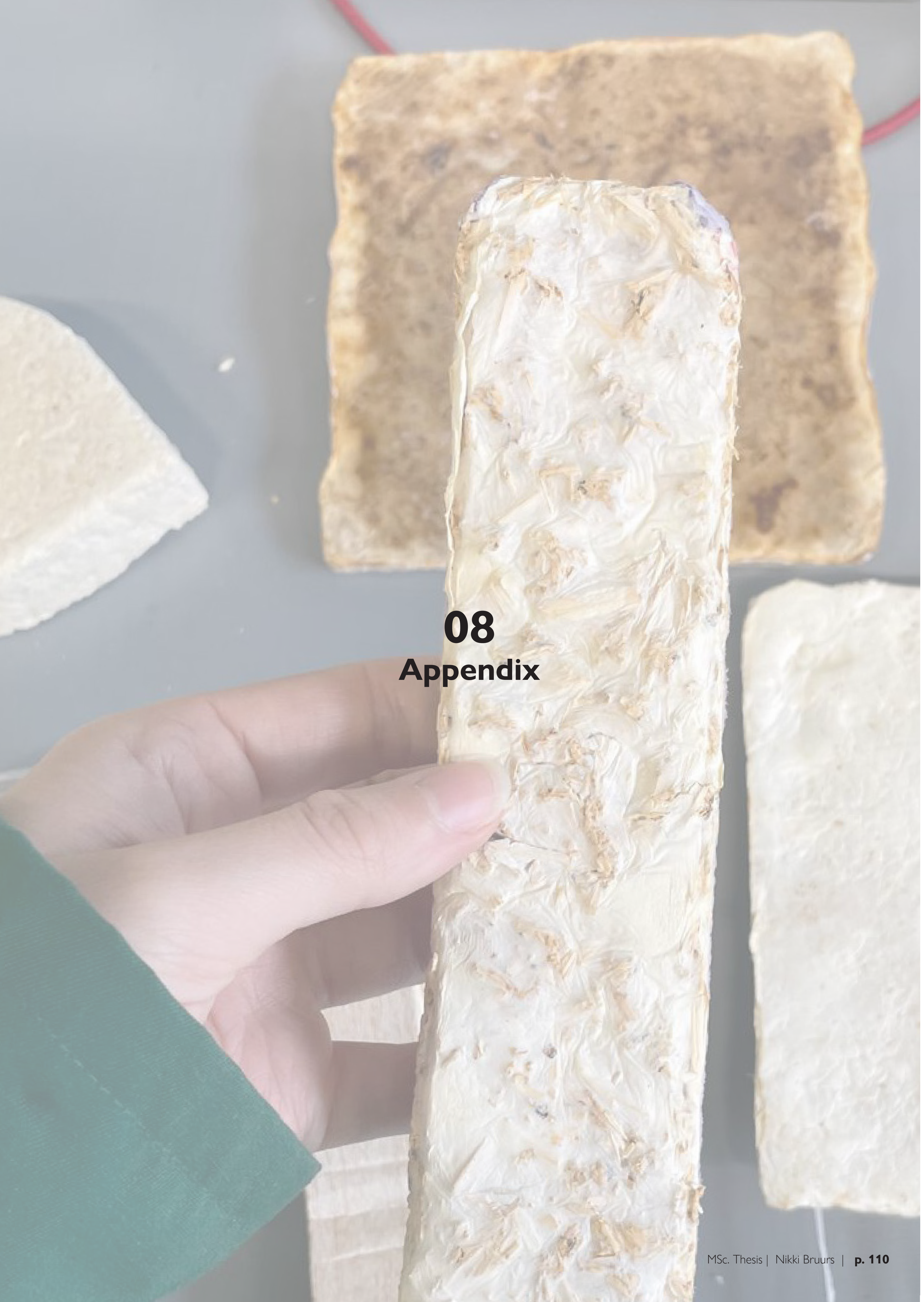
37. Temperature diagram during experiment 6, based on information provided from the app 'AranetHome', own work

38. Framework prototype components formwork, own work



08
Appendix

08 Appendix

8.1 Interviews and meetings

8.1.1 Interview with Omid Hajishirmohammadi at the BlueCity Rotterdam

1	**Who**	Omid Hajishirmohammadi	Mycelium expert in the Netherlands	Omid developed applications for structural mycelium, and is founder of 4 Earth 2 Mars.
2	**Where**	BlueCity, Rotterdam		
3	**When**	Friday 31.05.24		
4	**What**	1. Affordability	Normal brick: €0,90 Mycelium brick: €4,50	The mycelium can for now not be used in slums / poor places.
		2. CO2 negative production process	During production, mycelium needs a regulated room and an oven to bake after the drying process.	Only when the mycelium is produced in higher scale, it can be CO2 negative.
		3. Substrate	Weed (grows fast)	In the BlueCity they use weed as substrate for making mycelium products.
		4. Process	1. Disinfect	In the BlueCity they use a special station to disinfect everything that will be used during the production process and to mix the mycelium with the substrate.
			2. Dry	After this, there are temperature regulated stations in two different sizes to let the mycelium dry for one week.
			3. Bake	The mycelium can be bakes after one week of during. This step lasts 8 hours till one day, depending on the size of the product.
		5. Outcome	Optimal sized brick to use in space.	

Disinfection and mixing station

Growing cabins in different sizes

Smaller oven for baking process

Weed as substrate (left) and other substrates used (right)

Optimal sized and formed brick to use in space.

8.1.2 Interview with Anne den Hollander at Witteveen+Bos

1	**Who**	Anne den Hollander	Structural Engineer Witteveen + Bos
2	**Where**	Witteveen+Bos	Office in Utrecht
3	**When**	Monday 03.06.24	10:00 - 11:00
4	**What**	1. Compression	When a load-bearing wall or column can handle little to no tensile force, it is useful to add more compression force (from the ceiling/roof or upper floors, for example), to balance the moment.
		2. Moment	What kind of moment can the material handle? When building more round buildings as Hy-Fi in New York, the moment will also be less.
		3. VNK Statica 6.0	Used tool for calculations in construction at Witteveen+Bos.
		4. Application	Temporarily housing Temporarily pavilions Topping on existing buildings Replacement of timber construction - It might be a problem that the lifespan is too short for integration in construction, temporary construction could be the solution. - Demountability is not an important topic anymore when a temporarily structure is made from mycelium and is standing there for <30 years.
		5. Fire safety	30 - 60 minutes is required, is this the case with mycelium?

8.1.3 Seminar Jan Wurm at Aerospace Engineering

1	**Who**	Jan Wurm	Consultant at Arup Professor KU Leuven
2	**Where**	Faculty of Aerospace Engineering, TU Delft	Lecture Room D
3	**When**	Monday 17.06.24	10:45 - 12:00
4	**What**	1. Seminar	Reimagining materials: from sustainable to regenerative
		2. Bio-based materials	The material book, 2020 EMF Circular Economy Bio-based materials > Living materials
		3. Mycelium	Cooperation with Mogu: acoustic panels Timber mycelium pre-biofab panels Timber based sub-structure with magnets Mycelium = 3x more expensive than traditional acoustic materials
		4. Substrate	Fabric MyxSail Scaffold with mycelium on top: A lot of still air with insulating and acoustic values
		5. Reinforcement	Flexible timber veneer Leftovers of timber veneer: waste University of Kessel cooperation
		6. Structure	From itself mycelium is not strong enough When smart used it might be possible: - Distribute stresses - Smart growing process (with reinforcement) - It is stiff and hard - Into a system
		7. Acceptance and desirability	Different colour palette: not always acceptable Joints and connection parts: into a system Built-in zippers
		8. Later email contact with Jan Wurm	External mould growth: you need to ensure s sterile environment as much as possible, starting with sterilizing the substrate materials. All instruments and work surfaces that can come in contact with the materials during the handling need to be sterilized. You should wear gloves during handling. External mould indicates that contamination has happened at some point during the process, some species are more sensitive to contamination than others.
			Pressing: hot pressing after drying of panels is an established process to increase density and strength as a post-processing step. Pressing of substrate before the fabrication process will considerably slow down the process as the fungi need to "breath". In high density substrate you will find low growth rates.

8.1.4 Interview with Frank Huijben and Fran Ortega Exposito from MNEXT

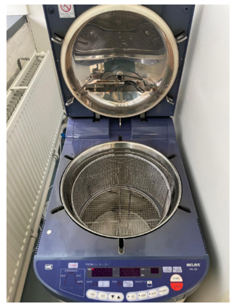
1	**Who**	Frank Huijben	Professor of Applied Sciences – Bio-based Construction, Avans Hogeschool & MNEXT
		Fran Ortega Exposito	Researcher Mycelium Materials Lectorate Biobased Building
2	**Where**	Avans Hogeschool Breda	Building LD, Room: LD222
3	**When**	Tuesday 27.08.24	10:30 – 12:00
4	**What**	1. Fungus	The decision has been made regarding the rate of growth. It is unlikely that fungi with a long growth period will be used in this industry, as they are not suitable to achieving high yields. Instead, the focus will be on selecting strains that exhibit rapid growth, thereby increasing the overall production. At MNEXT, Ganoderma Resinaceum is used as a spawn, however, oyster mushroom is also considered a potentially viable option based on the insights provided by Fran. For the spawn, they add 3 – 10% of the wet weight of the substrate.
		2. Substrate	Rapeseed straw.
		3. Growing process	It is of great importance to ensure that the inoculation process is conducted in an optimal environment with a high level of cleanliness, as any contamination from other fungi or bacteria could potentially disrupt the mycelium fungi. In this case, the mycelium is unable to dominate and because of that unable to grow on the substrate. After 5 days the mycelium is strong enough to withstand a less clean environment. The optimal conditions for fungal growth are in a dark environment. The latest research indicates that a day-and-night rhythm is also effective. Question: Why was the Monolito Micelio able to grow in the outside – not clean or dark- environment? Answer: They added a lot of mycelium spawn, so the spawn could always dominate additional fungi of bacteria.
		4. MycoHAB Namibia	Mycelium + Clay with panels on both sides to make it weather resistant MycoHAB Namibia harvests and crushes the ecologically destructive Acacia mellifera that is plaguing the country to provide a substrate for the mycelium to grow.
		5. Lifespan and EOL	The expected lifespan of mycelium is 30 years; however, numerous reference projects have shown that the expected lifespan is not always the actual lifespan, as observed in the XX project in Delft (expected lifespan: 20 years). One of the key challenges with mycelium is that it is still in the testing phase. However, TU Eindhoven is planning to explore its viability. The lifespan of mycelium is dependent on the surrounding environment, including: - Is it humid? - Is there a chance of infection? However, there are strategies to overcome these limitations, such as the use of (bio) coatings. When considering the longevity of a structure, it is essential to focus on the end of life rather than the lifespan. In cases where the lifespan is (probably) limited, the primary objective is to ensure that the structure is circular.
		6. Carbon neutral?	It should be noted that the incubation and production process is not carbon neutral in the laboratory setting. However, it is possible to achieve carbon neutrality at an industrial scale. However, it is also not a significant concern for this material to be carbon neutral, since it is a circular product.
		7. Water- and fire resistance	The white fungal part of the mycelium products is resistant to both water and fire, whereas the substrate is not. Therefore, the greater the amount of whiteness, the greater the resistance will be. According to Fran, there is no current fire certification for specific mycelium bio composite products in the market. In their experimentation they determined it is D-B. As mycelium bio composite materials can be produced from different fungi and fibers, it all depends on your ‘recipe’.

8.1.5 Interview call with Andy Cartier from Studio Cartier and Spore.nl

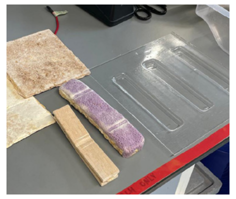
1	**Who**	Andy Cartier	Designer at Spore.nl and owner of Studio Cartier
2	**When**	Wednesday 02.10.24	11:30 – 12:15
3	**What**	1. Fungus	Pleurotus Ostreatus is a sensitive species + growth time is longer. Better choose Ganoderma or Trametes Versicolor: more resilient, faster growth and makes stronger connections. Order the fungi at kineco.bio. They use Ganoderma lucidum.
		2. Substrate	Hemp for the lamps, the rest is still confidential.
		3. Growing process	They make use of the Hedelcomposite from kineco.bio. Hedelcomposite is a mycelium substrate developed for grow it yourself purposes. They use Ganoderma spawn in combination with residual sawdust. After grown, this is the spawn you can combine with other fibrous substrates. Because the inoculation process already is started, the mycelium is pre grown and will grow faster and stronger on the additional substrate (within 6 – 7 days). It is also not too sensitive for the perfect environment. Add 10-15% spawn to 85-90% substrate. With this amount of spawn, the mycelium will overgrow contamination and will win the race against external molds and bacteria. Keep the process as simple as possible, since all the additional steps are also tricky with higher chance of contamination. Those steps will also make the process more expensive when applicated in industry.
		4. Experiments	They test compression, sheer and 3 point bending for sandwich panels. It is confidential why they use 3 point bending tests, so this may not be relatable for the graduation thesis testing.
		5. Pressing	It will influence the density of the material. There are 3 options: 1. Pressing before growing process (more dense material, slower growing rate); 2. Pressing halfway the growing process; 3. Pressing after the growing process, before drying. Cold-pressing will be the best solution, because then there is no additional energy used during the process.
		6. Additional flour	Add flour at the same time as adding the spawn to the substrate, at the beginning of the growing process. It will give the mycelium a kickstart to grow faster. In the end, this will speed up the process by approximate half a day (12 hours). But it will also give the material a more homogeneous appearance. This will be better for the attraction of the end product. The flour is not sterilized, but the flour will be only 1% of the total volume, so this will not be a problem since the other 99% is sterilized.
		7. Connection	In a previous video of Andy in 2021 they made use of wood as a connection part without using any glue or other external materials. The mycelium just grew on the wood and made connections. The method they used is confidential, so the question how this was managed is still there. When first baking the mycelium product to make it complete, it cannot grow anymore on another material connection like wood or textiles: look into references.
		8. Skin	After the growing process, the sample is removed from the mould and permitted to dry for a further two days, during which time an outer layer, or white skin, will form. The strength of the sample is significantly influences by the formation of this outer layer. If the mycelium composite samples are allowed to grow in a mould that has not the right dimensions (but larger), the samples have to be cut, resulting in removing the skin, which has a negative effect on the strength of the samples. Andy was unable to provide further details, as the information is confidential, but this outer skin layer is something that can be tested.
		9. Mould	RVS or aluminium is good. Plastic is the cheapest and also very good, but sometimes the mycelium wants to also bind with the plastic mould. Glass is best, but this is expensive and hard to find / make in the right dimensions.

8.1.6 Interview with Mrinal Chaudhury, PhD Candidate | Circular Bio economy | Airbus & TU Delft

1	**Who**	Mrinal Chaudhury	PhD Candidate Circular Bio Economy
2	**Where**	Aerospace Engineering, TU Delft	The lab of Aerospace Engineering where the mycelium composites are made and researched.
3	**When**	Friday 11.10.24	09:30 – 11:30
4	**What**	1. Fungus	*Ganoderma luc.,* because it is the most assured so far. Not guaranteed to show the best mechanical strengths. *Pleurotus ostr.* is food based, which makes it softer.
		2. Substrate	Hemp, fine sawdust, textile (cotton) waste. Straw did not work because the pieces are too big. Hemp and textile waste have yielded the best results (texture, relative homogeneity).
		3. Growing process step by step	1. Saturate the substrate with water; 2. Sterilize the substrate: Substrate in autoclave bag, seal with autoclave tape and autoclave it for 120 minutes (solid cycle); 3. Store sterilized substrate in fridge till you need it; 4. Biosafety cabinet: UV sterilize everything to use in the biosafety cabinet, then mix spawn (15%) + substrate + flour (5-10% of weight): mix super well. More spawn = faster growth. Too much = more flexible and foamy, too less will result in less strong samples. The flour helps with avoiding contamination, because it is hard for external fungi and bacteria to eat through the flour; 5. Incubate substrate in the autoclave bag for 2-5 days as required (wait for white growth); 6. Biosafety cabinet: Break the mycelium clumps in the bag, mix well. Let it grow in 27 °C with 70% - 100% humidity. Better mix = better results. Growth in a dark place is nice but not required. Tip: Put weight on sample to get dense growth, but still provide the sample with air; 7. Skin growth: Getting skin growth by letting the sample grow in more space will give better properties; 8. Drying & killing. This can be done in multiple ways to get different results (see figure below). Faster drying process will cause a loss in strength and the material will shrink because of loss in hydrophilic strength inside. Tensile strength will be slowly taken away when baking. 9. Processing: Cold press or hot press. The growing process will not be that big of a difference per substrate for the inside of a sandwich panel. The outside of the panel needs stronger directional fibers, like cotton or jute. Also the skin growth is important, even as the pressing or not pressing process (for densifying) and the drying process. So the post-processing phase makes a lot of difference.
		4. Mould making	The Indistrial Design faculty has a machine that produces negatives by vacuuming plastic moulds.

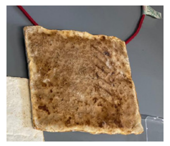




Stretchy & foamy ← Sample behaviour → Hard & brittle

Freeze dry	25°C (roomtemperature) 0% humidity 2 days	30°C 0% humidity 1 day	70°C 0% humidity 5 hours



8.1.7 Interviews at Witteveen + Bos
1. Shan He | Structural Engineer

1	**Who**	Shan He	Structural Engineer at Witteveen+Bos
2	**Where**	Witteveen+Bos	Office in Rotterdam
3	**When**	Monday 21.10.24	13:00 - 13:45
		Tuesday 05.11.24	10:30 - 11:30
4	**What**	1. Simple structure	Simplify the complex shaped structure to a simple structure to be able to know what kind of mechanical properties are necessary for the material. In this way you know what you are looking for in the numbers of the results from the compression and bending tests, therefore you also know which substrate + which fungi species to choose, depending on the results of the mechanical tests and the necessary values. The application can be changed, depending on the results of the testing. The simple shape closest to the complex shape is an arch. For an perfect arch you only need compression strength. Can it withstand the load of wind and rain? Or only self-load (dead load) when putting the structure inside (safe environment).
		2. Calculate panel or whole structure?	Because the whole structure is self-supporting (and so is the panel), it is not enough to just do some calculations on the panel. The whole structure must be taken into account. When designing one panel, you don't need to calculate the entire structure.
		3. Arch extention	From the initial point of an arch, you can extend the structure. An arch can be the base of the complex shape. When using bricks/blocks: need high compression strength & high stiffness; When using panels: need higher bending strength & more elastic. In case of a panel: it might be useful to add a material such as jute or cotton (as outer layer) for extra tension strength, like the steel is doing in reinforced concrete.
		4. Outcome compression tests	Define the elastic modulus (young's modulus) and the deformation value. F [N] / A [mm2] = σ [N/mm2] or [MPa] (stress)

2. Janet van de Wetering | Consultant Building Physics

1	**Who**	Janet van de Wetering	Consultant Building Physics
2	**Where**	Witteveen+Bos	Office in Rotterdam
3	**When**	Monday 06.01.25	17:30 - 18:15
4	**What**	1. Acoustics	The thickness of the material directly influences the effectiveness of sound absorption, with thicker materials providing greater benefits. This property is most advantageous at lower frequencies. In a larger room, a longer reverberation time is more easily tolerated than in a smaller room. In order for a material to achieve a high absorption value, it must possess either mass, porosity, or a rough texture. The rough texture is most effective for high frequencies, while a complex shape is more beneficial for lower frequencies.
		2. Waste managament building Voorhout	This project has not yet been realised; however, it is an office for waste management that has been constructed with a secondary steel construction and a fully bio-based facade. The partition selected for the rendering is situated between the cafeteria and a meeting room, necessitating sound-absorbing properties and a reduced reverberation time. The targeted reverberation period for this particular wall was set at 0.6 seconds. It is essential that the partition wall has an effective absorption value, given that the building does not have a suspended ceiling and thus no acoustic material is present in the ceiling.

8.1.8 Meetings with Fred Veer for mechanical tests and microscopic research, MSE lab and microlab, TU Delft

1	**Who**	Dr.ir. F.A. (Fred) Veer	Associate Professor of Material Science, TU Delft
2	**Where**	MSE Lab	Mechanical Engineering, TU Delft
		Microlab	Faculty of Architecture, TU Delft
3	**When**	Tuesday 08.10.24	10:00 - 10:30
		Monday 04.11.24	11:45 - 13:30
		Monday 18.11.24	09:30 - 11:30
		Wednesday 20.11.24	11:00 - 12:15
4	**What**	1. Dimensions samples	**Compression:** A cube of dimensions 20 x 20 x 20 mm, with a compressive strength of only 10 MPa, would require a load of 4000 N. The cube's size is determined by its compressive strength. The maximum load that can be applied is 80 kN, which represents 80% of the 100 kN range. Therefore, the objective is to find a cube that can withstand an 80 kN force. The minimum size that could withstand the specified force is 20 x 20 x 20; thus, to conserve material, this is the size of the samples. (20 x 24 x 20 is also an acceptable alternative to 20 x 20 x 20, as this dimension was achieved more efficiently during the mould-making process.)
			Bending: Bio composites: 4 point bending test: Length >120 mm 3 point bending test: 50 mm < length < 120 mm 1/10 length ≤ Height & Width ≤ 1/5 length Height ≤ Width when application is panel, floor, brick, roof, etc. Height ≥ Width when application is for example a beam or a bridge. Dimensions using: Panel, so Height ≤ Width 100 x 20 x 15 mm
			A minimum of 5 and a maximum of 10 samples per material combination is required to obtain a sufficient number of results for calculating an accurate mean.
		2. Samples Jute and Cotton (CJP, CJG, CCP and CCG) (BJP, BJG, BCP and BCG)	It is not advisable to test these samples, as they are not a homogeneous unit. The results would be inconclusive due to the lack of consistency in the tensile strength values. While the samples may demonstrate adequate compression properties, they would likely fail when subjected to a minimum tensile loads. Therefore, testing them under compression is a viable option, although the results may not be meaningful. Testing them under three-point bending is not feasible as the samples lack the necessary stiffness.
		3. Three-point bending test	The initial distance (span) was set at 80 mm, based on the fact that the length of the sample is 100 mm. The force was applied at a speed of 5 mm per minute. BHP1 was subjected to the first application of the bending force, yet even with minimal force exerted, the sample underwent deformation, leading to cracking. Consequently, the span length was reduced to **40 mm**. The outcomes of the initial sample test, therefore, proved inconclusive. The results of the test were more useful from this point onwards (since BHP2), but the force applied was still so small that fluctuations were visible in the graph. Usually, these fluctuations are not visible because the force is too large for this; therefore, the graph is more zoomed out. However, in this instance, they were visible because of the low forces applied. The order of testing was as follows: first, the BHP samples; second, the BSP samples; and third, the BSG samples. The BHG samples were not tested due to the lack of mycelium development within these samples. Prior to the BSG4 sample, the maximum deformation was set at 10 mm. However, from BSG4 onwards, this was changed to 'until they break', given that the final samples demonstrated greater resilience and were able to withstand greater force and deformation. The point 'until they break' appeared to be 14 mm, as illustrated in the graph in 4.5.5.
		4. Inconsistent test results	The distributed results per sample made it impossible to also test whether the results were better or worse when the area with the thickest skin was on top or on the bottom when applying the bending force. The results of the various tests were found to be **highly inconsistent**, thereby making comparison between them difficult. A number of factors may have contributed to this inconsistency. - The mixing process; - Environmental conditions (differences in temperature, humidity, etc.); - Post-processing
		5. Distribution per sample	Given that the samples were cultivated in the same environment at the same time and underwent the same post-processing techniques, it can be concluded that the inconsistencies observed in the material distribution within each sample were likely due to a suboptimal mixing of the different materials (sawdust or hemp, mycelium, and flour).
		6. Digital 3D microscope research	The digital 3D microscope is capable of providing a more detailed and accurate visualisation of specimens with three-dimensional structures, such as mycelium-based composite samples and their cross-sections. In this field of investigation, the process of breaking the samples through bending tests not only allows for the analysis of the samples' structural properties but also facilitates a deeper understanding of the underlying factors that contribute to their rapid failure. **Hemp + *Pleurotus ostreatus*** The distribution is poor due to the size of the hemp particles, which results in numerous weak spots with only mycelium threads. Additionally, the surface exhibits a considerable number of black spots. Upon closer observation, hairs originating from these black spots are evident, indicating the presence of a different thread type. This thread differs in texture and thickness from the mycelium itself. **Sawdust + *Pleurotus ostreatus*** The sample demonstrates more optimal distribution due to the observation of smaller and finer particles. The substrate is divided in closer contact with one another, resulting in a reduction of weak points with only mycelium (given that the substrate provides the mechanical strength). Additionally, a gel-like substance was observed. The hypothesis is that this is sawdust and water that are in a transitional phase. Furthermore, there are more black spots visible on the surface than in the cross-section. The spots are not connected to the sample and are situated in a more loose manner on the surface, above the 3D network consisting out of very fine threads looking for connection with other mycelium threads. **Sawdust + *Ganoderma lucidum*** The same structure of 3D thin mycelium threads is visible, indicating a search for a connection with each other. Additionally, the external mould is visible within this sample, appearing to be more orange-like than previously observed. Upon closer observation, it becomes evident that this is not an in-depth contamination, but rather a surface phenomenon. It is unclear whether this is a component of a biological process or an instance of contamination. However, it has a fibre structure identical to that of the mycelium, but with a different colouration. The distribution within this sample was notably more uniform, with minimal weak spots. A notable observation was a shiny area that captured attention. The hypothesis is that this is a minor contamination of different layers over each other, though it is unclear if this is external mould or another contamination.

8.2 Reflection Questions

8.2.1 Graduation process

1. How is your graduation topic positioned in the studio?

The integration of mycelium-based composites in structural (load-bearing) building elements represents an optimal alignment with the objectives of the Building Technology master track at TU Delft. This is due to the fact that the use of MBC (Mycelium-Based Composite) is consistent with the main themes of the track, namely sustainability, innovation, material performance and interdisciplinary research. This innovative, entirely bio-based panel made of MBC as main material offers a forward-thinking solution to the important challenges facing the building industry, particularly in terms of circularity and sustainability. Moreover, its potential as a structural component represents an optimal choice for the studio, contributing to the development of more sustainable and efficient building technologies.

2. How did the research approach work out (and why or why not)? And did it lead to the results you aimed for? (SWOT of the method)

The research approach involved an initial phase of literature reviews and case studies to gain a deeper understanding of the material. This was used to identify areas of research that were under-researched, thereby identifying potential gaps in the existing literature. This was followed by own research based on a lot of experiments, with extra literature review when necessary and with numerous interviews with experts. This approach proved highly effective, although it did occasionally result in the discovery of a better method or material use only after the completion of an experiment, which resulted in the addition of new experiments to the list, requiring time and, in some cases, this was not feasible within the available timeframe. While this was occasionally inconvenient, it was unavoidable and ultimately resulted in more optimal research outcomes at the end.

3. If applicable: what is the relationship between the methodical line of approach of the graduation studio (related research program of the department) and your chosen method?

It seems reasonable to suggest that the method selected is one that is typically used in thesis research. The main difference is that ongoing meetings with experts continue to provide access to new information, even after the literature review phase. This new information would have been beneficial to have gained before the experimentation phase (so in the literature review phase), in order to make more informed choices for the experiments. However, it was still useful to have access to this information afterwards, in order to make minor changes to the next experiment.

4. How are research and design related?

The thesis research is based on literature reviews, case studies, experiments and model studies with physical models and references. The prototype and final design are developed and designed based on the findings during the whole graduation process: The literature review, which identified fungal species and substrates for further testing to assess their ability to grow. The results of the growth experiments have led to the selection of the most appropriate substrate + mycelium part and species for testing in compression and tension. The outcomes of these mechanical tests have identified the optimal combination of materials for use in the panel formwork. Consequently, the use of material for the panel design is based on all of these findings. The design itself is based on references and physical model studies.

5. Did you encounter moral/ethical issues or dilemmas during the process? How did you deal with these?

During the development of my thesis, I was confronted with a number of moral and ethical issues. A challenge that required attention was the necessity to guarantee the sustainability and environmental impact of the materials employed as a substrate. My goal was to create a product that was aligned with circular principles, so I tried to use waste stream materials in my experiments whenever possible. However, this was not always a viable option. In some instances, it was necessary to obtain new materials, and there were occasions when an experiment involving these materials resulted in suboptimal outcomes, leaving behind unused material that was no longer applicable to the project. This presented a challenge to my commitment to sustainability, but I attempted to minimise waste wherever feasible. However, this was not always possible, particularly with regard to the substrate and mycelium orders, which were sometimes only available in large quantities. To illustrate, the mycelium delivery of the hedelcomposite Ganoderma lucidum was only available in packages of 10 kg. This amount of material was not needed for this research, so it is a waste of material to have so much left over. In the case of the grain spawn of the Pleurotus ostreatus, it was also available in smaller packages (1kg), which allowed me to better estimate how much was needed and reorder it when it was almost empty.

A further challenge occurred when consulting with experts in the field. Many of these experts had access to valuable insights, but were required to maintain confidentiality in accordance with their professional obligations. While they were able to provide some general information, the specific reasoning behind their advice was often withheld. This meant that I was required to place trust in their guidance without having a full understanding of the underlying logic, which was challenging at times. I was able to navigate this challenge by combining the input from these experts with my own independent research and literature research in order to make informed decisions.

8.2.2 Societal impact

1. To what extent are the results applicable in practice?

In order for MBC to be employed in the building industry, it is essential that it complies with a number of safety and performance standards, including load-bearing capacities and fire resistance. Although the results indicate a combination of materials that exhibits the greatest strength (sawdust + *Ganoderma lucidum*), it remains not comparable to concrete, steel, or wood. Further testing is required, for instance in the form of reinforcement, prior to integration into the structural building industry.

Consequently, the switch is made within this graduation process from a more application-based approach (focussed on structural applications) to a material-based approach, with the objective of identifying the optimal application for this specific material. This switch in approach ensures that the outcome of the thesis is more applicable in practice, as a panel does not require the same mechanical properties as an alone-standing structural component.

2. To what extent has the projected innovation been achieved?

A crucial innovative aspect of the prototype is the utilisation of mycelium as an adhesive, functioning as a bio-based binder. This approach eliminates the necessity for chemical adhesives, making the material 100% bio-based and sustainable. This represents a unique advance in the application of mycelium, which demonstrates its potential for use in contexts beyond those for which it has traditionally been employed.

Additionally, the panel is composed of a single main material, mycelium, which represents a second significant innovation. By employing mycelium as both the structural formwork and the binding component, the panel illustrates the potential for creating a composite material that is multifunctional, sustainable, and circular.

It is important to note that certain aspects of the panel remain under development. One aspect is scalability, which refers to the process of creating the panel on a larger scale while maintaining uniformity and cost-effectiveness. This is an area that still requires further exploration, particularly given that the current panel is composed of multiple layers, which can be costly to install in the correct sequence and quantity of material. Another aspect that requires further investigation is long-term performance testing. This refers to the durability of the panel in diverse environmental conditions, such as humidity, and it refers to an evaluation of the lifespan of the material itself.

3. Does the project contribute to sustainable development?

The material is fully biodegradable, therefore ensuring that it does not contribute to a build-up of waste. Upon reaching the end of its life, the panel is capable of undergoing natural decomposition, thereby providing further support for the achievement of sustainable development goals. Also the project makes use of waste stream materials as substrates, thereby reducing the necessity for non-renewable resources and avoiding the disposal of agricultural or industrial by-products in landfills. Although it was not always possible to do so in practice on this small scale, this approach demonstrates the potential for integrating waste streams into material production.

4. What is the impact of your project on sustainability (people, planet, profit/prosperity)?

In terms of people, the project aims to raise awareness of sustainable materials and their potential applications. It strives to motivate individuals and industries to integrate more bio-based practices and to explore the multifunctional potential of biobased materials.

From a planetary perspective, the project emphasises the use of renewable materials, like mycelium and waste stream substrates, in order to reduce dependence on non-renewable resources and minimising environmental impact. Additionally, at the end of its lifespan, the material undergoes a natural decomposition process, which prevents the build-up of waste in landfills.

With regard to profit and prosperity, the project presents new opportunities within the sustainable materials market, offering eco-friendly alternatives to traditional building components. This has the potential to stimulate economic growth in green industries. The utilisation of durable yet biodegradable materials is aligned with the increasing consumer demand for sustainable products, thereby ensuring long-term profitability and market relevance for companies that decide to adopt this technology.

5. What is the socio-cultural and ethical impact?

The project contributes to the creation of healthier living and working environments by eliminating the use of harmful synthetic chemicals, such as those found in traditional adhesives. This supports the ethical goal of protecting human health and well-being. Also some people may have sceptical or negative perceptions of using fungi as a building material, perceiving it as unappealing or unclean. To address this, it was essential to design a prototype that is not only functional but also aesthetically pleasing. By creating a visually appealing and modern design, the project helps challenge misconceptions and encourages acceptance of mycelium-based materials.

Ethical challenges also included working with experts who were only able to share limited, non-confidential information. This was sometimes inconvenient, as it was necessary to assume that they were telling the truth without presenting arguments to support their statements. However, this was a necessary and unavoidable aspect of this project.

6. What is the relation between the project and the wider social context?

The project engages with the broader social context by addressing significant issues such as climate change, resource shortages, and waste management. The project offers a natural, biodegradable material as an alternative to traditional building materials, thereby supporting sustainability and global goals for better resource use. The use of waste materials and reduction of carbon emissions make the project eco-friendly and promote responsible production. The project also creates local employment opportunities as the bio-based material is made from local waste streams and mushrooms, and demonstrates that mycelium-based materials can be both useful and visually appealing. By inspiring new ideas and challenging people's perceptions of sustainable materials, it encourages greater acceptance of eco-friendly solutions in innovative building products and design.

7. How does the project affects architecture / the built environment?

Mycelium's ability to act as both a building material and a bio-based binder opens up new possibilities for architectural design. Its renewable and biodegradable nature also meets the growing demand for greener building practices and materials that minimise environmental impact, and encourages the integration of bio-based technologies into everyday architecture.

The use of locally sourced or waste stream substrates can also promote regional supply chains and support a circular economy. This improves the environmental and economic sustainability of building practices.

8.2.3 Own questions

1. What was the impact of the graduation internship at Witteveen + Bos

I experienced the internship at Witteveen + Bos as a very positive contribution to my thesis. From the start, I benefited from regular meetings with my supervisor Nader Merhi, who provided guidance and assistance throughout the process, answering my many questions on short terms and offering helpful advice when I was stuck. Furthermore, the rest of the team 'Building Physics & Circularity' also helped me to resolve various issues, including how to make numerous calculations in Excel in a more efficient way and they provided me with the some useful tools and devices to assist me with the experiments and make them easier and more efficient. It was particularly beneficial when I encountered challenges and needed guidance on a short-term basis. Furthermore, they provided me with a number of useful suggestions regarding the content and structure of the presentations, as well as the thesis document.

In addition, throughout the entire process, I had the opportunity to speak with numerous experts from Witteveen + Bos, which enabled me to gain further insight and knowledge on specific topics. In addition, I was given the opportunity to use one of their projects as a contextual example, with a goal to demonstrate the viability of the final design in a practical setting.

But beyond lots of help, knowledge and advice, the internship at Witteveen + Bos facilitated a positive experience during the graduation period. There was always the option of reaching out to anyone for advice or a boost of motivation, as well as the opportunity for social interaction at the coffee machine. It would be my strong recommendation that every graduate student consider taking part in such an internship.

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