WASTE NOT: BUILDING MATERIALS FOR A SUSTAINABLE FUTURE

Implementation of circular economy and living mycelium materials for architecture

ANASTASIA GLOBA[1], RACHEL LEE[2] and ARIANNA BRAMBILLA[3]
[1,2,3] *The University of Sydney, Australia.*
[1]*anastasia.globa@sydney.edu.au, 0000-0002-4749-5675*
[2]*rlee5517@uni.sydney.edu.au,*
[3]*arianna.brambilla@sydney.edu.au, 0000-0002-8494-7861*

Abstract. The escalating climate crisis and diminishing resources call for a radical shift from high-carbon building materials to more sustainable alternatives. This paper investigates the potential of mycelium, a living biomaterial, in creating sustainable architecture from household waste, addressing resource depletion, and contributing to a resilient built environment. The study's unique contribution is the practical application of household waste to produce mycelium composites for building materials, supporting a circular economy. In an experimental study, sixty samples with differing substrate-to-mycelium ratios were systematically analysed for weight gain/loss, shrinkage post-drying, health of growth, mould contamination, and aesthetic qualities. The findings demonstrate the feasibility and limitations of utilising local waste and living materials in architecture, addressing the research question concerning mycelium's potential in sustainable and localised construction. This paper details the experimental findings and outlines the next research phase, advancing the innovative application of mycelium in the field, and their adoption within wider communities.

Keywords. Mycelium, Living Materials, Circular Economy, Sustainable Materials, SDGs

1. Introduction

The current state of building materials, predominantly used in existing and newly constructed architecture, is characterized by a high embodied carbon footprint. This is a significant concern considering the escalating climate crisis, rapid population growth, and diminishing resources. The construction industry, a major contributor to global greenhouse gas emissions, is under increasing pressure to reconsider its reliance on traditional, carbon-intensive materials (Berrang-Ford et al, 2011). These challenges call for an accelerated and radical shift in building design and practices. The United Nations Sustainable Development Goals (SDGs), particularly Industry Innovation and Infrastructure (9), Sustainable Cities and Communities (11), and Responsible

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Consumption and Production (12), highlight the importance of this transformation (SDGs, 2023). The shift towards sustainable practices in the construction industry is not merely a response to these challenges. Circular economy and innovative sustainable materials, sourced from renewable or waste resources, can play a pivotal role in this transition. These materials require less energy-intensive manufacturing processes, reducing greenhouse gas emissions, conserving resources, and minimizing environmental impact. Particularly if the materials can be produced or sourced locally.

In recent years, the research agenda in the field of sustainable materials has seen an increasing interest in living biomaterials, such as mycelium. These organic materials feed on composites found in nature to create strong, fibrous forms with unique structural and aesthetic qualities (Gough et al., 2022; 2023). Their resilience, rapid growth, and the circular economic aspect of respawning and recycling, coupled with a low-expense production pipeline, make them an attractive alternative to traditional building methods. This study builds on the growing body of research on myco-materials, aiming to demonstrate the feasibility and practical implementation of using commonly available household waste products to create viable substrates for growing building materials such as insulation and external and internal finishes using mycelium composites. Conducted in Sydney, Australia in July 2023, the experimental study tested a variety of waste products within different substrate-to-mycelium ratios, with 66 samples produced for the first stage of the study (60 testing waste types/ratios and 6 extra samples testing surface finishes/aesthetics) and 68 samples for the second stage.

This paper reports on the production methods and results of the first stage of the experimental study, which demonstrated the feasibility and limitations of using local waste and living materials in architecture. The research contributes to the innovative application of mycelium in the field, laying the groundwork for future exploration of the thermal, acoustic, and structural qualities of myco-material composites produced from locally available household waste.

2. Background / Mycelium as a Sustainable Material

Mycelium is the vegetative part of fungi (mushrooms) consisting of a tightly knit network of fine filaments (hyphae). It is capable of absorbing nutrients from its immediate environment and creating solid forms. Mycelium is an emerging living/biomaterial in sustainable design and architecture, as it can create strong, fibrous forms, and has the potential benefit of recycling organic waste (Stamets, 2005). Its unique structure gives myco-material composites compressive strength and structural properties similar to synthetic foams, while myco-materials can also positively impact building sustainability by reducing embodied energy (Jones et al., 2020). One of the recent studies showed that compared to traditional bricks the industrial production of myco-materials can significantly reduce greenhouse gas emissions (Stelzer et al., 2021).

In recent years mycelium has been adopted for a wide range of applications, including packaging, design objects (Attias et al, 2020), furniture, building structures (Elsacker et al, 2021; Wei et al., 2023) and even landscaping (Margolis & Robinson, 2007). Previous studies have tested the growth of mycelium-based materials to replace traditional bricks and various structural elements, including large-scale mycelium structures (Dessi-Olive, 2022). Extending the scale even further, recent research has explored mycelia for topographical landscape applications, utilising robotic onsite fabrication and 3D print extrusion of myco-material structures (Colmo & Ayres, 2020).

Mycelium, with its potential for reducing carbon emissions, recycling waste, and creating resilient and environmentally ethical built environments, holds great promise for sustainable construction (Vallas, & Courard, 2017). However, a significant knowledge gap exists in its feasibility for practical use and community adoption. Much of the existing research and experimentation with mycelium focused on design applications and form/structure exploration, being conducted in controlled environments, relying on sophisticated manufacturing methods. These approaches are valid and greatly contribute to the knowledge in the field, however, they can have substantial implications on the sustainability metrics of the output products and their lifecycle, which can potentially offset the environmental benefits of using mycelium as a sustainable material.

This study aims to address this knowledge gap by challenging the prevailing reliance on high-end fabrication equipment and highly controlled production pipelines. The true potential of mycelium as a sustainable material can be unlocked by developing simple, low-cost, and accessible production methods. Adoptable for diverse communities, particularly those with limited access to resources and equipment. This study seeks to democratize the production of mycelium-based materials, making it accessible to a broader range of users. This approach not only expands the potential user base of mycelium but also aligns with the principles of a circular economy, where waste is minimized, and resources are kept in use for as long as possible. Ultimately, this research aims to contribute to a more sustainable and inclusive approach to construction, where communities are empowered to create their own environmentally friendly building materials.

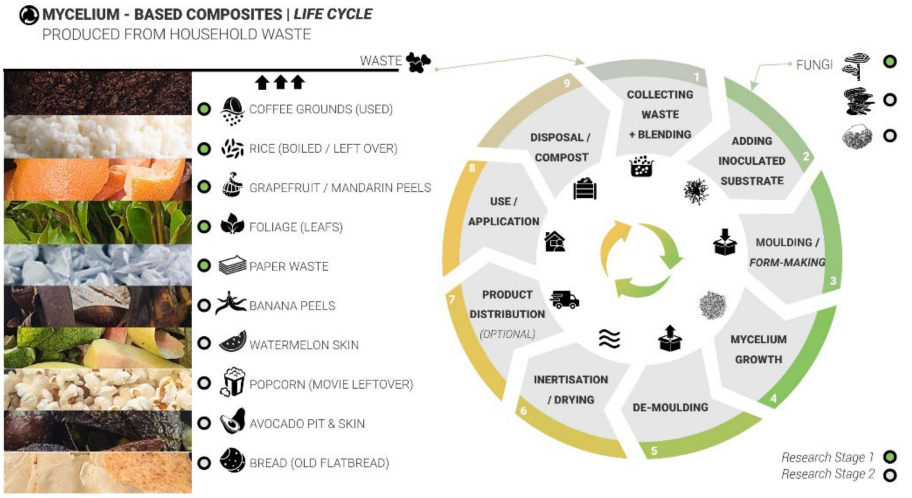

Figure 1. Life Cycle Diagram for the myco-materials produced from household waste.

Figure 1 illustrates the proposed life cycle diagram for the proposed waste-to-myco-materials. As shown in the diagram the use of myco-materials also allows to dispose of unwanted myco-material products locally by simply composting them.

3. Methodology and Experimental Set-up

Substrates for the study comprised easily accessible local household waste, such as used coffee grounds, leftover rice, foliage, fruit peels, and paper. Additional equipment included 750ml rectangular plastic takeaway containers, breathable tape, a thermal and humidity sensor, 4 L round plastic basins, large black plastic bags, a digital scale, and plastic gloves. Six 2.2 kg Australian Reishi (Ganoderma Steyaertanum) mushroom kits sourced from 'Aussie Mushroom Supplies' and kept refrigerated prior to their use. 60 test samples were created, containing incremental mycelium substrate-to-waste ratios of 10%, 25%, 50%, 75% and 90%. Where the percentage number referred to the content of the initial Reishi substrate. A separate control set without any added waste was used as a control group. The substrate samples were placed in takeaway containers (moulds) - to provide the intended shape, the lids had holes drilled in and were covered with breathable tape to enable ventilation and access to moisture that is required for mycelium growth. Rectangular takeaway plastic containers were used to form a standardised mould, which allows for versatility in future uses such as bricks or a tiled façade. These containers could be easily re-used again as form-making moulds.

The containers were covered in dark closed spaces to control humidity, and temperature and prevent fruiting of the mycelium. The internal temperature and humidity averaged 20 degrees Celsius (C) and 50% relative humidity. Hydration was periodically performed using warm water sprays to foster ideal growing conditions. The growth of the test samples occurred over 15 days after moulding. When colonised (after mycelium growth) the samples were extracted from the containers and stored in breathable clear plastic bags, placed in a cool dark environment to allow growth of an exterior mycelium skin. Once the external skin was confirmed to have a leathery texture (1-2 days duration), the test batches were stored in a warm/hot space to dry and prevent any further growth (inertisation). Finally, the samples were air-dried in an interior environment for 3+ months.

4. Results

4.1. WEIGHT AND VOLUME LOSS

This section presents the results from the first stage of the study, reporting the failure rate, weight over time and total weight and volume loss after drying (Figures 2 and 3). The 4.2 subsection expands on the material autonomy, visual appearance, and aesthetic qualities of produced samples.

Following a growth period of approximately 14-15 days in temperatures averaging 20 degrees Celsius, and humidity of 50%, the samples were relocated to dry at around 30 degrees Celsius and 50% humidity (Figure 2, 3).

All test batches displayed similar patterns in percentage weight loss over time, with minimal loss during the mycelium growth period, a sharp decline during inertisation, and minimal loss after the initial drying stage. The total weight loss throughout the experiment for most substrates was at around 60%, however, the Mandarin peels test group demonstrated a greater weight loss percentage of 70-80%. The control group containing zero additional substrates had around 65% weight loss, suggesting that there was a consistent weight loss trend measured across all test samples.

The percentage of volume loss, in contrast, varied significantly among the samples, with an average of 24.6% for the Coffee, 35.2% for the Rice, 40.8% for the Mandarin, 26.6% for the Leaf, and 34.5% for the Paper test groups. The control group had an average of 24.5% volume loss which is similar to the Coffee and Leaf subsets. The greatest volume loss occurred in the Rice, Mandarin and Paper test groups, this likely happened due to the initial high water content of these waste materials; that would have evaporated during inertisation and air-drying stages. The volume loss results for the Paper test group are likely due to the shape of the shredded paper creating air pockets. It was expected that the mycelium would fill in those spaces as it grew, however, that did not occur, as the paper was likely too dry and thus harder to colonise for the mycelium. Instead, the paper shrunk with the mycelium during the inertisation stage.

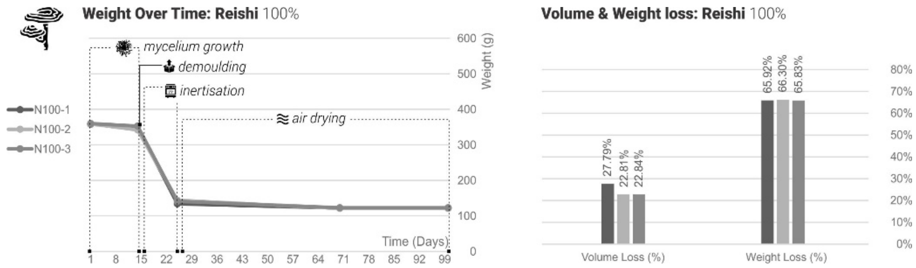

Figure 2. Reishi 100% test group: Weight over time. Total Volume and Weight Loss

Prior to and following the inertisation (stop growth) stage, a significant portion of the test samples were discarded due to mould growth or structural instability. The removed samples are indicated in the tables in Figure 3 with an "x" marker. From 60 samples 31 exhibited mould growth. The type of mould varied across different waste subjects. Green/white furry mould was prevalent in mixtures containing mandarin peels, whereas mixtures containing rice showed black dusty mould. Mould growth occurred at both the growing phase and the drying phases. Any samples demonstrating significant mould growth were disposed of.

The results show that across all test groups, the samples with 50% or below 50% waste proportion have successfully formed mycelium, showing signs of healthy growth and lack of mould and contamination. The red circles with crosses on the diagram indicate a lack of mycelium forming after 2 weeks or mound/contamination during the growth phase (Figure 3). The contamination/failure during the inertisation/drying - as indicated by black circles with crosses in the diagram (Figure 3) shows that a considerable number of samples failed (exhibited mould growth) during the initial drying stage. This was particularly significant for the Rice test group. For this experimental stage, the samples were dried at a temperature above 30 C degrees good air circulation, but no exposure to the direct sunlight.

The follow-up test showed that when the samples are initially 'sun-dried' - exposed to the sun during the initiation stage, the success rate increases dramatically to 100% success rate. Learning from this experience, during the second stage of the experiment, all samples were initially dried in the sun, and no failure was recorded during this myco-material production stage.

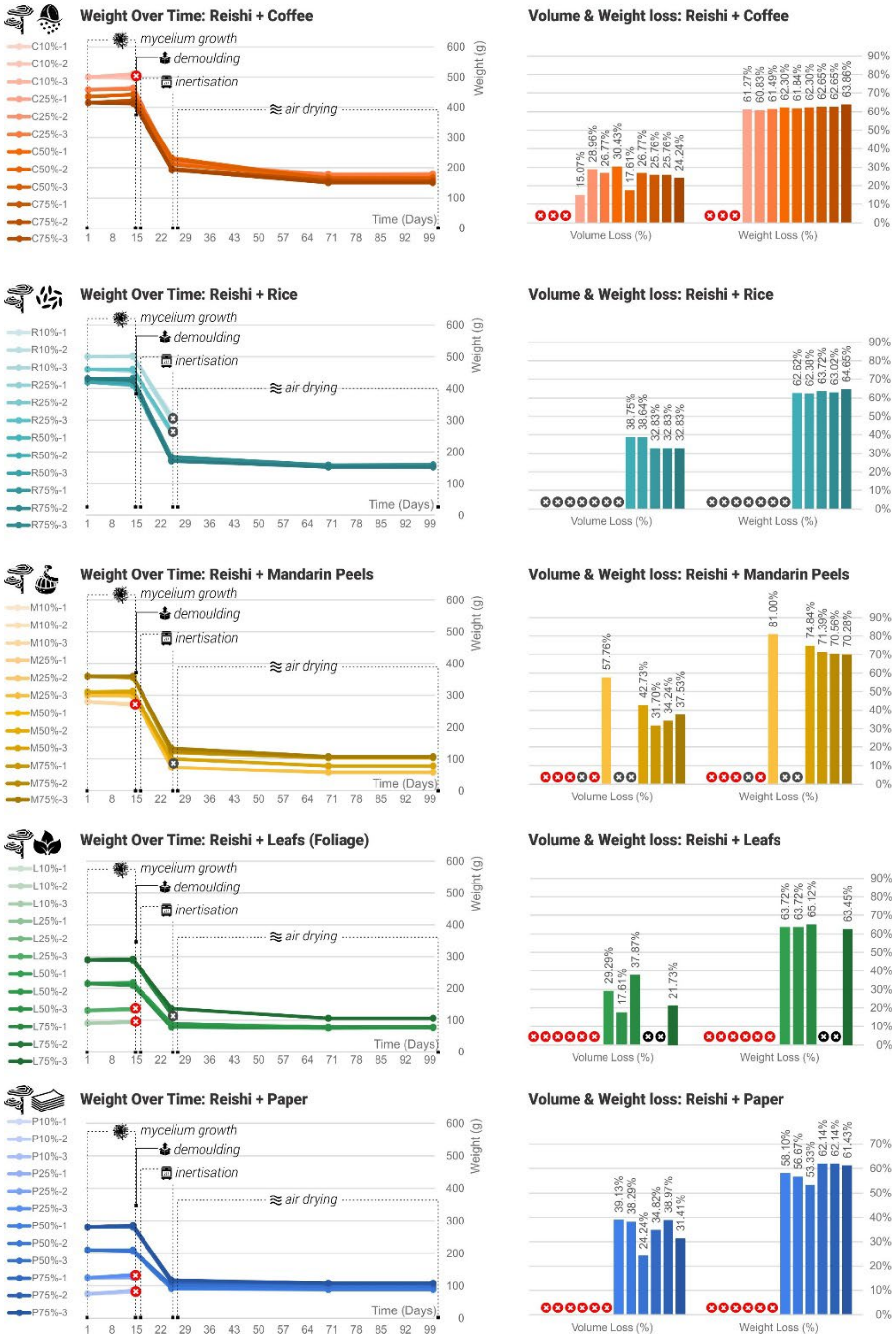

Figure 3. Reishi + household waste test groups: Weight over time. Total Volume and Weight Loss

4.2. AESTHETIC QUALITIES OF THE MYCELIUM COMPOSITES

One of the unique features of mycelium-based products is the autonomy of the material itself. While the overall shape can be greatly controlled by the implemented production method (moulds, extrusion etc.), the volume and weight loss can be calculated based on available experimental data, informed by studies such as this; the outer surface of mycelium is much harder to control. The seemingly identical samples exposed to the same conditions can have drastically different visual appearances. Figure 4 illustrates the range of myco-material samples produced for this study. Although all samples were grown at the same temperature and humidity using the same type of moulds, and the base substrate was inoculated with the same Reishi mushroom - the samples all look distinctly different. Some samples have a more homogenous white skin consistent with Reishi mycelium hyphae colour (Figure 5, C). Other samples have different light or dark brown patterns on them that can be typically observed on Reishi mushroom fruit bodies and spores (Figure 5, B, E).

Figure 4. Test samples (all test groups)

In addition to being a resilient type of mushroom that is well suited for growing living materials, Reishi has the unique characteristic of being able to grow a distinctive 'skin' layer on the surface of its output form. This skin has the functional purpose of creating a protective layer on the surface of the mycelium composite. Our study showed that this outer skin grows best when the samples are unmoulded and kept in dark humid environments, with temperatures between 18-28 C and usually takes 1-2 days to grow a solid layer of skin. When the samples are left to grow outside of the moulds for longer periods they tend to (a) 'grow out' greatly deviating from the target shape or (b) more likely to start growing a fruitbody. Different types of exposure, for example, a plastic wrap touching parts of the sample surface (Figure 5, B, E, F), and substrate composition, such as high content of foliage closer to the outer surfaces (Figure 5, D), can have a significant effect on the appearance of the mycelium skin. These findings imply that it is possible to achieve greater control over the appearance and aesthetic qualities of the myco-material skin, suggesting a fascinating topic for future research.

Figure 5. Aesthetic and surface quality attributes across the samples

5. Discussion, Future Research and Conclusion

The results of this study strongly indicate that it is indeed possible to produce myco-materials using substrates with up to 50% of household waste proportion (volume); and without requiring any sophisticated technologies, controlled sterile environment, or specialised equipment.

Unlike existing studies, none of the waste components that were used in the study were sterilised for the second stage of this research project, to better simulate real-life scenario applications. The lack of sterilisation undoubtedly influenced the results increasing the risk of initial contamination and mould. However, these results also illustrate the feasibility of the proposed approach, proving that the findings of this study can be easily extended to wider communities and industries. Lessons learned from the inertisation/initial drying stage informed the methodology implemented for the second stage of this research project (i.e. introducing sunlight exposure), which can significantly improve the success rate during the drying stages.

Comparison across the test groups shows that coffee grounds, cooked rice and paper waste are less likely to cause contamination during the mycelium growth stage. Foliage and fruit peels on the other hand are more prone to failure due to mould growth when the waste ratio exceeds 50% of the myco-material substrate.

All test samples exhibited a similar weight over time patten, continuing to lose weight for up to 56 days past demoulding. After this period samples stabilise their weight and volume, as illustrated by previously produced samples that we continuously observed for over 4 years installed indoors.

In terms of total weight loss (initial weight/volume vs 85+ days past de-moulding), samples with coffee waste samples exhibit consistent outputs and tend to retain most of their initial weight and volume with 15-28.9% weight loss and 60.8-63.8% volume loss. Samples with rice waste showed similar volume loss with 62.3-64.6% and a slightly higher weight loss percentage (32.8-38.7%). The Mandarin waste test group showed the highest extremes of weight and volume loss, with 57.7% and 81% respectively.

The limitations of the 1st stage of this study were: a) only 5 groups of tested household waste types, and b) tested using only one type of fungi - Reishi mushroom mycelium. To overcome these limitations the second stage of this study included different types of mushrooms including, Reishi, a range of Oyster mushroom species (Grey -, Winter Chocolate-, White- and Blue Oyster) and Lion Mane mushroom. The range of waste was expanded to include: coffee, banana, grapefruit, mandarin, passionfruit and hedge leaves, watermelon, rosemary, avocado peels and pits, popcorn, and old flat bread (Figure 1).

The force pressure tests for all the samples were conducted to better understand the structural performance of waste-based myco-materials. Although the reporting of these results falls outside of the scope of this paper (due to the page count limitation), the findings will be communicated in the follow-up manuscript(s). It is planned to extend the performance testing to the hygrothermal analysis, acoustic qualities, and thermal and fire resistance assessment. The study will follow the established methodology in the field (Walter & Gürsoy, 2022; Jones et al., 2018; Gough et al., 2024) comparing between types of waste and different waste proportions.

In conclusion, this study showcases the potential and feasibility of using local household waste and mycelium, a living biomaterial, to produce sustainable architectural materials. The findings demonstrate that it is feasible to convert household waste into building composites, supporting waste reduction and circular economy. This research further reinforces the avenue in sustainable construction, highlighting the need to consider innovative, locally sourced, and low-impact materials, that could be available for a wide range of communities, addressing the climate crisis and resource depletion.

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