From Waste to Resource: A Design-to-Fabrication Approach Integrating Recycled Wood - Mycelium Mixtures for 3D Printing in Architecture

Miran Calmanovici[1], Achiya Livne[2] and Shany Barath[3]
[1,3]Technion - Israel Institute of Technology
[2]Ben Gurion university of the Negev
[1]miran.c@campus.technion.ac.il, 0009-0005-1761-6391
[2]achiyali@post.bgu.ac.il, 0000-0001-8289-7410
[3]barathshany@technion.ac.il, 0000-0003-0776-7389

Abstract. This research investigates the development of Recycled Wood and Mycelium Mixtures for sustainable 3D printing in the Architecture, Engineering, and Construction (AEC) sector. The AEC industry is responsible for a large share of global resource consumption and waste generation, underscoring the need to integrate natural, bio-based materials into construction practices. By utilizing wood waste from local industrial streams and combining it with mycelium (Ganoderma lucidum), the hyphal network of fungi, this research aims to offer a sustainable alternative to conventional materials while reducing environmental impact. Although progress has been demonstrated through casting, 3D printing remains a challenge. Two experiments were conducted to evaluate the effects of different gelling agents and wood particle sizes on material performance in liquid deposition modeling 3D printing. A mixture of psyllium husk and corn starch were identified as the most effective gelling agents and demonstrated potential printability within a large-scale setup, for bio-based architectural components with high wood waste content. The research highlights the need to improve printing formulations in alignment with fabrication protocols to advance sustainable architectural performance through robotic additive manufacturing.

Keywords. 3D wood printing, mycelium-based composites, additive manufacturing, bio-based materials, circular construction, biodesign

1. Introduction

The Architecture, Engineering, and Construction (AEC) industry accounts for over 30% of global resource consumption annually (Orhon & Altin, 2020), underscoring the critical need to reduce raw material use and integrate recycled waste, such as wood waste, into the AEC sector. Although wood is recognized as a sustainable, bio-based construction alternative, the current wood supply chain lacks circularity, leading to substantial waste and environmental concerns. Commercial practices combine wood with synthetic binders that are often toxic or non-environmentally friendly (Kumar &

Leggate, 2022). Combining wood waste with natural binders such as mycelium, the hyphae network of fungi, offers a promising approach to creating bio-based materials. While traditional wood and mycelium casting techniques using formworks are effective and can achieve performance goals, such as enhanced acoustic and thermal properties, they are often resource-intensive and generate significant waste, with formworks typically ending up in landfills once the growth process is complete (Ghazvinian & Gursoy, 2022). This paper focuses on developing a suitable recycled wood and mycelium mixture (RWMM) for liquid deposition modeling (LDM), a promising extrusion-based technology for 3D printing. The study examines multiple formulation mixtures composed of locally sourced wood sawdust from industrial waste, Ganoderma lucidum mycelium, a gelling agent, and water. It addresses production challenges and material properties related to extrusion-based 3D printing and aims to facilitate a systematic design-to-fabrication workflow. This includes pre-fabrication, fabrication, and post-fabrication protocols to advance the integration of wood waste into the design of architectural components through mycelium-based binders.

2. Background

To reduce dependency on virgin materials in the AEC industry, particularly wood, which contributes significantly to construction waste, biobased materials derived from local wood waste streams have emerged as a viable alternative. Wood flour, a commercial byproduct from wood chips, sawdust, and shavings, can be integrated into additive manufacturing (AM) for the production of 3D components with minimal material loss. As AM has the potential to reduce environmental impact compared to traditional methods, LDM emerges as a leading technology for 3D printing wood-based extrusion pastes (Cohen et al., 2024) . Moreover, it shows potential to produce structures that support mycelium growth through a higher surface-to-volume ratio compared to traditional molding processes (Elsacker et al., 2022). This method, paired with computational manufacturing techniques, has the potential to support the development of RWMM in architectural applications.

2.1. WOOD WASTE IN 3D PRINTING

A common approach to 3D printing wood involves combining sawdust with binders, which can be processed in various printing methods. Typically, wood is blended with thermoplastics in AM applications (Krapež Tomec & Kariž, 2022). However, these composites face constraints related to the wood content amount, usually remaining below 40 wt% (Kariz et al., 2018). Another approach is Individual Layer Fabrication that combines wooden particles with powders and resin such as cement, gypsum, starch or polymeric methylene diphenyl diisocyanate and spreads them in layers over a build plate. Water is then selectively applied to activate the binder in specific areas, allowing the object to be built up layer by layer as each new layer is bound to the previous one (Buschmann et al., 2024; Henke & Treml, 2013). An alternative approach is LDM, a technique that enables large-scale printing of paste-like materials such as clay and concrete. Recently, LDM has been adapted for 3D printing with wood combined with binders (Rosenthal et al., 2018). Various binders have been explored, including ureaformaldehyde resin; however, it limits wood content to less than 30% (Pitt et al., 2017). In contrast, methylcellulose, a water-based binder derived from renewable resources, has emerged as a bio-based alternative (Bierach et al., 2023), allowing for a significantly higher wood content of up to 89% (Rosenthal et al., 2018). The choice of binder is crucial, as it affects not only the strength and durability of the final product but also its environmental impact, opening the door for innovative materials such as mycelium to be explored as sustainable alternatives.

2.2. PRINTABILITY OF MYCELIUM BASED MIXTURES

Mycelium, the root-like structure of fungi, has emerged as a promising natural binder for 3D printing, particularly LDM (Elsacker et al., 2022). When combined with organic substrates, the mycelium grows into a lightweight, foam-like material. The 3D printing of mycelium-based materials at an architectural scale are limited and include Pulp Faction (Goidea et al., 2020) and a column by Blast Studio (Lovely Trash Column, n.d.), that created column-like structures. These projects used a two-phase process: initial growth of the substrate and the mycelium in bags followed by 3D printing of components that were stacked to achieve the vertical structure. The columns were printed in segments due to printer size and layer limitations. While they showcase the potential of 3D-printed mycelium composites, detailed information on the fabrication process is limited.

Recent studies are exploring methods to enhance 3D-printed structures using mycelium. One method involves printing wood-PLA composites and injecting mycelium at specific points to provide localized reinforcement (Alima et al., 2022). Another approach, combines mycelium with clay and sawdust, allowing the mycelium to grow within the printed form and reinforce the structure naturally (Jauk et al., 2022). Additional research by Mohseni et al. has focused on developing mycelium-based composite from cardboard, psyllium, and water, while defining a workflow to mitigate contamination (Mohseni et al., 2023). Soh et al. describe the development of 3d printed 30x30 mm extrudable mycelium paste under non-sterile conditions (Soh et al., 2023). Another preliminary study demonstrated the feasibility of 3D-printing a biomass-fungi mixture using a WASP 2040 printer (WASP, Italy), examining how psyllium husk affects printing quality and the rheological properties of the mixture (Bhardwaj et al., 2021). Elsacker et al. investigated the potential for large-scale 3D printing of mycelium-based materials using beechwood particles, testing various gelling agents to optimize printability (Elsacker et al., 2022). However, this study highlighted the challenge of printing unsupported geometries, which was addressed by temporarily reinforcing the cylinder model with wood dust, enabling the printing of up to seven layers reaching 24 mm height. Despite these advancements, gaps remain in understanding the long-term durability of 3D-printed mycelium-based materials and their scalability for larger applications. Furthermore, there is limited knowledge on the combined effects of wood type, particle size, and varying gelling agent compositions on material printability. As a result, key aspects of material performance and scalability remain unexplored.

3. Materials and Method

The methodology employs a comparative approach to examine relationships between material mixture components and printing variables for the selection of RWMM formulations within a tailored design-to-fabrication workflow (Fig. 1). Two experiments were conducted: the first, evaluated three gelling agents, while the second, examined two wood types and three particle sizes. The pre-fabrication stage involved designing a customized printing toolpath using Rhinoceros 3D and HAL Robotics in Grasshopper. Work areas and tools were sterilized with 98% ethanol, and gelling agents and wood particles were sterilized in a pressure cooker to ensure optimal conditions for mycelium growth in the printing mixture. Three gelling agents—psyllium husk, corn starch, and arabic gum—were selected from literature (Elsacker et al., 2022; Modanloo et al., 2021) as favourable for 3D printing and combined with beech wood from local industrial waste (particles 0.6-1.0mm), fungal spawn (G. lucidum grown on hemp shives, Lambert Spawn, Netherlands), and water.

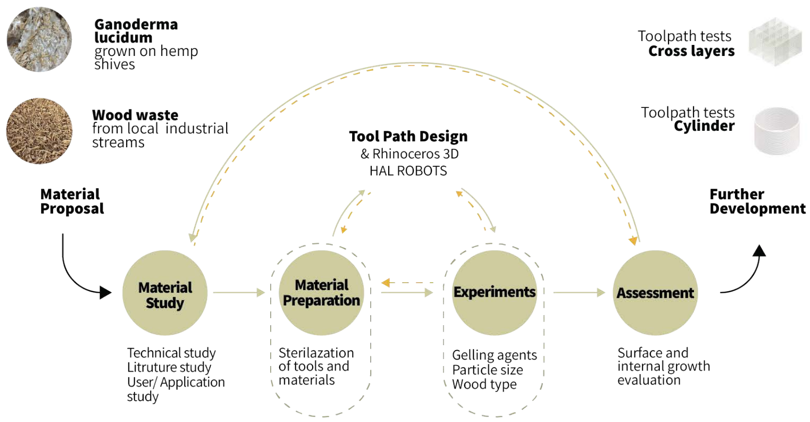

Fig. 1 - The methodological diagram outlines a workflow for examining relationships between material mixture components within the Design-to-Fabrication process

During the fabrication stage, a UR5e robotic arm (Universal Robots, Denmark) equipped with a WASP LDM extruder (10 mm nozzle, 3D-printed in PLA) was employed, with all equipment sterilized beforehand. The selected gelling agents were evaluated based on five parameters: mycelium growth speed, buildability, adhesion, extrudability, and aesthetics. Each printed model was assigned a score from -1 to 1 for all parameters, where -1 indicated failure, 0 indicated a pass, and 1 indicated success. These parameters were evaluated and tested at eyesight, touch and qualitative observation. Mycelium growth speed and buildability were categorized as quantitative parameters and graded using a defined scoring system. Buildability was rated based on the number of printed layers, where 0–2 layers scored -1 (failure), 3–5 layers scored 0 (pass), and six or more layers scored 1 (success). Mycelium growth speed was rated by the time required for a visible full skin growth, with growth within 14 days scored as

1, growth taking more than 14 days scored as 0, and no growth scored as -1. The models were monitored over a period of 18 days, with photographs taken every 24–48 hours during the initial growth phase and every 24–72 hours in the later stages.

3.1. GELLING AGENT FORMULATION COMPARISON EXPERIMENT

In the first experiment, Gelling Agent Formulation Comparison, three gelling agents, psyllium husk, corn starch, and arabic gum, were tested in identical formulations containing 15 wt% gelling agent, 15 wt% beech wood, 10 wt% G. lucidum spawn, and 60 wt% water. The components were mixed to create a paste for comparative analysis. A small sample of each paste was placed in a petri dish to evaluate the effect of each gelling agent on mycelium growth (Fig. 2). Additionally, the viscosity and extrudability of each mixture were tested manually using a pastry bag, simulating the conditions of 3D printing with a robotic arm. When observing that a gelling agents failed to extrude from the pastry bag and in attempt to enhance the viscosity of the formulation, a small percentage of psyllium husk was added (12 wt% arabic gum, 3 wt% psyllium husk).

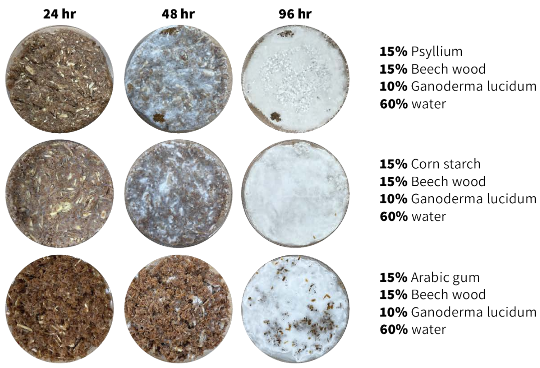

Fig. 2- Comparison of mycelium growth on various potential gelling agents in petri dishes to evaluate the impact of each agent on mycelium development

In the second part of the experiment, selected mixtures of psyllium husk and corn starch were tested in a 3D printing setup. The initial setup included a 10 mm nozzle size, 8 mm layer height, 2000 revolutions per minute (RPM) in clockwise (CW) direction, and a pressure of 2 bar, with adjustments to RPM in CW and air pressure levels made as needed for each mixture. The printed model followed a cross-layer printing path within a 100 mm x 100 mm x 100 mm volume. The gelling agents were tested individually and in combination at various ratios: 100% psyllium, 25% psyllium / 75% corn starch, 50% psyllium / 50% corn starch, 75% psyllium / 25% corn starch, and 100% corn starch.

3.2. WOOD TYPE AND PARTICLE SIZE COMPARISON EXPERIMENT

In the second experiment, the selected gelling agents mixture was tested with both oak and beech wood, along with two larger particle sizes (0.8 - 1.4 mm and 1.6 - 2.0 mm), to evaluate their impact on mycelium growth and surface colonization. The two wood types were used in the same toolpath model and newly determined ratios based on previous gelling agent test results. This formulation included 7.5 wt% corn starch, 7.5 wt% psyllium, 15 wt% wood particles, 10 wt% G. lucidum spawn, and 60 wt% water. Three models were printed for each wood type (Fig. 3). As in the first experiment, the printed models were monitored for up to 18 days, with photos taken every 24 to 48 hours during the initial growth phase and every 24 to 72 hours afterward. These photos were compared to gain a deeper understanding of how particle size influenced mycelium growth speed. Additionally, the printed models were cut open to observe internal mycelium growth, assessing how far the fungi had penetrated into the material, and how is it affected by the particle size. Each formulation was printed three times per model to ensure statistically reliable results. The comprehensive evaluation purpose is to identify the optimal particle size that enhances both surface colonization and internal mycelium penetration. To further assess and challenge the selected formulation, a cylindrical model (radius: 50 mm, height: 100 mm) was printed using the final beech wood and oak wood formulations.

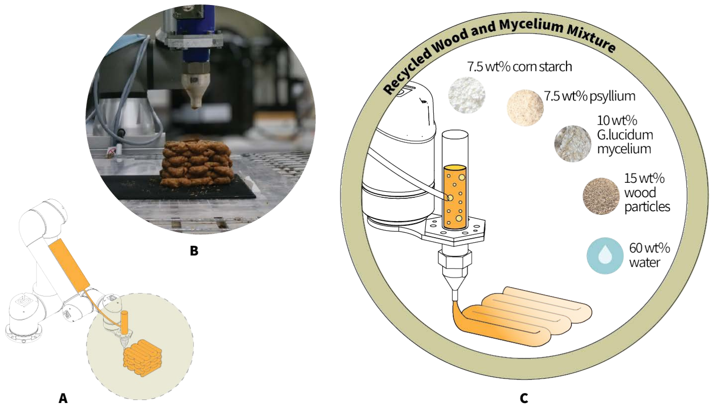

Fig. 3 - (A) 3D printed model toolpath; (B) Printed model using a 50% psyllium / 50% corn starch gelling agent ratio with the printing setup parameters;(C) The printed formulation

4. Results and Findings

4.1. GELLING AGENT COMPARISON

The results showed that psyllium husk and corn starch performed well as gelling agents for RWMM. Their properties allowed for model buildability, extrusion, and a sufficient layer adhesion, making them suitable for the LDM setup. Conversely, arabic gum did not function effectively in this formulation and was unable to produce a printable paste. Although adding psyllium improved the mixture's viscosity, the paste still showed inconsistencies in extrudability and compromised form accuracy in the final printed structures. Therefore, only psyllium husk and corn starch were selected for further experiments, while arabic gum was excluded.

Testing the extrudability of the 100% corn starch mixture revealed that excessive air pressure compacted the material, leading to fluid loss and blockage between the tank and the extruder, making the formulation unprintable. The other mixtures, however, exhibited appropriate buildability, consistent extrusion, and strong layer adhesion, making them suitable for the LDM setup (Table 1). After monitoring the initial 72-hour growth phase, mycelium growth rates appeared consistent across the four different printed samples. Based on these results and the findings from the earlier phase of the experiment, the 50% psyllium / 50% corn starch mixture was selected as the formulation for the next experimental stage.

GELLING AGENTS' COMPARISON

	MYCELIUM GROWTH	BUILDABILITY	ADHESION	EXTRUDABILITY	AESTHETICS	TOTAL
100% cs	-	(0 layer) -1	-1	-1	0	-3
75% cs / 25% ps	(12 days) 1	(8 layers) 1	-1	1	-1	1
50% cs / 50% ps	(12 days) 1	(8 layers) 1	1	1	1	**5**
25% cs / 75% ps	(12 days) 1	(5 layers) 0	-1	1	0	1
100% ps	(12 days) 1	(2 layers) -1	-1	-1	0	-2

Table 1 - Comparison of corn starch (CS) and psyllium (PS) as gelling agents, assessing different percentages of each on the printability of the paste according to five predefined evaluation parameters: mycelium growth speed, buildability, adhesion, extrudability, and aesthetics

4.2. WOOD TYPE AND PARTICLE SIZE COMPARISON

Results in the second experiment showed that wood type did not significantly impact the paste's printability in particle sizes 0.8 - 1.4 mm and 1.6 - 2.0 mm. However, surface colonization of mycelium varied slightly: after 72 hours, the beech wood models showed more extensive colonization than those made with oak. An additional 48 hours of observation revealed that the oak models had mostly caught up, reducing the initial difference in colonization (Fig. 4).

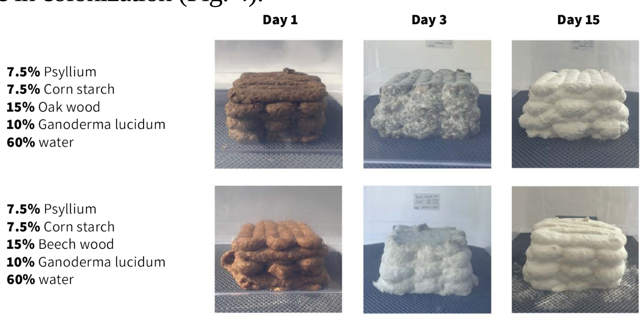

Fig. 4 - Surface colonization of mycelium on two wood types (beech and oak), 0.8 - 1.4 mm particles size, observed at 24 hours, 3 days, and 7 days.

Initial extrusion tests suggested that a 12 mm nozzle might be needed to accommodate the larger particles; however, further testing demonstrated sufficient extrusion with the original 10 mm nozzle, which was therefore retained. Same as in the first phase, no significant differences in printability were observed between beech and oak wood particles sizes 0.8 - 1.4 mm and 1.6 - 2.0 mm. Following 15 days of monitoring, all models displayed similar rates of mycelium growth and surface colonization, regardless of wood type or particle size.

In the final phase of the experiment, two cylindrical models were successfully printed without the need for support materials. The first cylinder (R: 50 mm x H:100 mm) printed with the previous formulation using particle sizes of 1.6–2.0 mm, maintained its structure without any distortion. The second cylinder was printed with unfiltered particle sizes ranging from approximately 0.4 - 30 mm. However, during the printing of the second model, issues with pumpability arose, requiring adjustments to the water content in the mixture. The revised formulation consisted of 6.25 wt% corn starch, 6.25 wt% psyllium, 12.5 wt% wood particles, 9 wt% G. lucidum spawn, and 66 wt% water. Following this adaptation, the second cylinder, like the first, successfully retained its structure. These results demonstrated the formulation's ability to produce buildable geometries without external support (fig. 5).

Fig. 5 -(A) The 3D-printed cylinder model using 0.4–30 mm particle; (B) printed with 1.6–2.0 mm particle sizes.

Results from cutting the models in half to evaluate internal mycelium penetration revealed that particle size did influence the amount of visible mycelium growth. However, insufficient porosity in the models restricted internal colonization, with mycelium growth primarily observed on the outer surfaces rather than within the internal structure. Overall, these results underscore the formulation’s viability for sustainable 3D printing applications, providing a foundation for further exploration of functional properties. The adaptability of the 7.5 wt% corn starch, 7.5 wt% psyllium, 15 wt% wood particles, 10 wt% G. lucidum spawn, and 60 wt% water mixture, combined with either beech or oak wood particles, demonstrates its potential for creating complex, self-supporting structures with minimal material waste and high wood waste content. Additionally, the consistent mycelium growth and colonization across wood types and particle sizes suggest these mixtures could be customised to a range of biobased architectural components designed for acoustic and thermal performance that are known properties of wood products.

5. Conclusions

This study demonstrates the feasibility of RWMM for large-scale LDM 3D printing, showcasing mycelium as an effective binder for wood waste in biobased materials. Through two printing experiments, a mixture of psyllium husk and corn starch was identified as promising gelling agents, while wood type did not significantly influence printability, mycelium growth, or surface colonization. The research established protocols for 3D printing with G. lucidum mycelium, emphasizing the need for defined workflows in RWMM applications for architectural components. Unlike commercial methods such as Mogu's molded acoustic panels (muvobit, n.d.), this study explored AM with RWMM, offering a flexible and sustainable alternative.

Results demonstrated RWMM's potential for unsupported cylindrical printing, eliminating the need for support structures required in similar studies (Elsacker et al., 2022). The ability to print unsupported cylinders highlights enhanced structural integrity, positioning RWMM as a strong candidate for architectural-scale applications. Future research will focus on refining formulations and optimizing computational toolpath designs to meet specific architectural objectives, such as improved acoustic absorption and thermal insulation in wood-based components. This work underscores the potential of integrating wood waste and mycelium into architectural design via LDM, offering a sustainable alternative to traditional building materials in computational robotic manufacturing.

Figure 6 - Printed models after full inoculation and drying.

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