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ADVANCEMENTS IN THE CRAFT OF GROWING STRUCTURES WITH MYCELIUM-COMPOSITE MATERIALS

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ABSTRACT

This paper presents advancements in architectural-scale design and fabrication techniques of mycelium composite materials. A series of experiments and prototypes are presented in this paper which explore myco-materials in their intermediate stage of cultivation when they are alive and flexible. The prototypes were made through novel *hang-dry* methods, which permit myco-materials to take forms otherwise not possible or inefficient using typical casting, or formwork-based approaches. The craft and complexity of cultivating fungi-based structures will be discussed, the background and development of the novel methods will be detailed, and the limitations associated with growing myco-structures will be reflected upon.

KEYWORDS

biomaterials, sustainable construction, mycelium, myco-materials, myco-fabrication, structural design

INTRODUCTION

Documented global trends show that lifespans of buildings are rapidly decreasing, while more than ever the construction industry still primarily uses materials that are mined and manufactured with energy-intensive processes, and often cannot be repurposed or recycled. It was recently reported that the average lifespan of buildings in China is 34 years (Liu et al. 2014), and 25 years for residential buildings in Japan (Wuyts et al. 2019). In 2018 the Environmental Protection Agency reported that the United States generated 600 million tons of construction and demolition waste (EPA, 2018), with about 24 percent of that going to landfill. Although in some contexts economic and cultural factors justify the use of energy-intensive materials for permanent assemblies, data suggests buildings will continue to be increasingly impermanent. Thus, there is a critical need for new low-energy and renewable building material systems that divert building and demolition waste from landfills and offset the impact of short lifespans of buildings. Adopting new materials that lessen the impact of the architecture, engineering, and construction industries on climate change is a challenging, but necessary endeavour. Candidate materials must have a commercial scale of production for other applications to ensure quantity, quality, and consistency. Importantly, *the way such new materials are used to design and build at architectural scale cannot be assumed.*

Fungi-based materials have gained significant attention because they are renewable, require very little energy to produce, and ultimately compostable – if so desired. Using processes nearly identical to mushroom farming, “myco-materials” are produced as a composite of lignocellulosic agricultural waste fibres, bound by fungal mycelium - the vegetative filaments of fungi (Stamets, 2005). Myco-materials have become an international enterprise and are produced at commercial scale for animal leather alternatives, packaging and insulation materials, and as an alternative material for other products that use plastics, foam, or styrene. In recent years several pavilion structures have demonstrated the potential of large-scale applications. This paper takes a critical approach to and presents advancements in design and fabrication techniques of fungi-based materials used for large scale structural design applications, which have previously lacked in diversity, beyond compression structures assembled with bricks or blocks, large monolithic castings, or 3D printing-based approaches. Innovation with this material is possible, but only through radical experimental development in myco-fabrication techniques. In this paper, a series of experiments and prototype structures are presented challenge previous assumptions about the formal and structural capacities of myco-materials. The main area of inquiry explored myco-materials in their intermediate stage of cultivation when alive and flexible (almost gelatinous), which facilitates growing forms of structures that were previously un-predictable or impossible. The MycoMatters Lab, directed by the author of this paper, oversaw the cultivation and fabrication of the prototypes with graduate research assistants in the College of Architecture Planning and Design at Kansas State University. The experiments were intellectually supported through collaborations with architects, engineers, computational designers, and fungal biologists. This paper will detail the intellectual background and methods of the novel myco-fabrication methods being proposed, discuss the craft and complexity of cultivating fungi-based structures at large scale, and reflect upon the limitations associated with growing myco-structures.

BACKGROUND TO MYCO-STRUCTURES

Mycelium Composite Materials

Myco-materials are making significant impacts in the bio-material industry due to their unique and variable properties which have facilitated their use in diverse contexts. Myco-materials are currently produced at industrial scale by companies like Ecovative, and Mycoworks who hold patents on different forms of production. Commercial success of myco-materials has been seen in applications including packaging materials (Holt et al. 2012, Mushroom Packaging), interior products such as lampshades and planters (Grown.Bio), flooring and acoustical panels (Mogu.bio), and currently the most successful is animal leather alternative textiles (Forager, Bolt Threads, Mycoworks). Mushroom-leather products are made through proprietary processes that harvest pure mycelium either in liquid cultures or from “solid-state” (Gandia, et al., 2021) trays of live substrate. The research in this paper is focused on building material applications of composite fungal biomass, which is both an in-put and by-product of solid-state-solid leather cultivation processes.

The matrix of mycelium composite materials consists of lignocellulosic agricultural waste fibres such as wheat, distiller’s grains, hemp herd, corn husk, or wood sawdust, bound together by an entangled web of fungal mycelium. Consisting of webby, hollow tubes called hyphae, mycelium is a chitin-based binding biopolymer. Nearly any shape can be grown by packing fibres that are inoculated with a living mushroom (often from the phylum Basidiomycetes) into a mould or formwork. The limitations for growth are biological and environmental. The most important precautions are proper sterility to avoid contamination or competition with other organisms, access to food and nutrients, maximal darkness, and access to warm, humid air. As such, very little energy input is needed for their cultivation. Myco-materials are typically grown in non-cellulose-based material mould and must have at least on side that is porous and permits the fungi to breathe. For large scale applications, an important consideration is that at certain thicknesses, mycelium does not grow sufficiently. Beyond 150mm of thickness there is a risk that the fungi dies too soon due to lack of air; presenting an opportunity for contamination. Provided that mycelium has sufficiently grown and bound to the lignocellulosic substrate, they are dried to stop the growth (Beyer, 2016) resulting in a material that resembles expanded polyurethane or polystyrene foam. Due to the complexities growing myco-materials, it is challenging to control the final density and consistency of mycelial growth, whereby the associated material properties (whether mechanical, thermal, acoustical, or other) are only somewhat predictable and understood to be a reported average. Different combinations of mycelium strains and fibrous substrates (hemp, corn husk, or wood sawdust, for example) yield a range of bio-composites with varying properties of structural integrity, density, thermal conductivity, moisture resistance, and visual quality (Elsacker et al. 2019). Studies have reported on such mechanical qualities (Girometta et al, 2019), the impact of moisture (Appels et al. 2019), acoustical properties based on mycelial growth (Hsu et al. 2021), and their biodegradability (Van Wylick et al., 2022). While myco-materials are relatively weak (0.1 – 0.2 MPa on average without mechanical compaction) and are assumed to work best in compression, they also have a high strength to weight ratio. As such, through advantageous material placement, large-scale and even long span structures are theoretically possible. Furthermore, myco-materials have a known a flame spread resistance comparable to gypsum, and low thermal conductivity which further reinforces their potential as a building material.

Myco-Structures

In the context of large-scale structures that use mycelium composite materials, only some use mycelium in a load-bearing capacity. An early structural application called “Myco-tectural Alpha”, was built of bricks grown from reishi mushroom cultures, dried, and stacked into a small self-supporting catenary barrel vault (Mok, 2012). Other structures have used a similar approach based on the production of bricks or blocks grown in custom-made moulds, actively dried, transported to site, and often assembled with the assistance of temporary formwork and other scaffolding structures. Notable examples include the 40-foot tall “Hi-Fi” tower (Saporta, 2015), and the MycoTree (Heisel et al. 2018). 3D printing techniques in the context of myco-materials have been widely demonstrated and bring about the exciting prospect of growing parts of structures without the need for plastic moulds (Goidea et al. 2020; Soh et al. 2020). Due to the difficulty of managing large living colonies of myco materials, 3D printed myco-structures have been made of units less than 1m x 1m x 1m. A hybrid technique called “bio-welding”, or “myco-welding” involves assembling structures with discreet living parts and growing the parts together under correct environmental conditions. The technique has been used to make small-scale structures (Modanloo et al. 2021), furniture (Dahmen, 2017), and a large triumphal arch in an art installation by David Benjamin and Engineers at ARUP (Saporta, 2019). Myco-welding has also been used for making mycelium blocks for use with robotic-controlled abrasive wire cutting (Elsacker et al. 2021). Beyond these discrete-element construction techniques, design and research efforts have been made to grow materials monolithically in-situ. Small scale examples have been published (Adamatzky, A. et al. 2019) which employ a woven cellulose-based exoskeleton. The only published example of a large-scale structure is the Monolito Micelio (Dessi-Olive, 2019). Grown from a one-ton colony of mycelium-stabilized hemp, the vaulted myco-structure was a critical response to the observed monotony of brick/block-based myco-fabrication methods previously accomplished. The pavilion demonstrated that myco-materials can inherit myriad fabrication logics at large scale including rigid board formwork, and flexible fabric formwork, common to cast-in-place concrete.

MYCO-SHEETS METHODS: DESIGNING WITH FLEXIBILITY

This paper argues that innovation with myco-materials is possible, but only through radical approaches for designing, growing, and assembling these materials into new and previously un-predictable structural forms. A unique myco-fabrication technique is proposed here, which generates complex curvature in flat mycelium composite sheets (myco-sheets) by hang-drying them from precise support points and eliminates the need for wasteful moulds or formwork. Myco-materials are mostly agnostic to form and will grow into any space available to them, provided lignocellulosic food and the proper warm, dark, and humid growing conditions. The techniques described in the previous section all are based on containing loose fibres while hyphae grow and bind those fibres together. Small objects such as bricks and blocks used for construction can be grown in reusable plastic moulds made by common vacuum-formed sheets or a Fused Deposition Modelling (FDM) 3D printer. Larger and more complex shapes require robust, custom-made scaffolds that negotiate and regulate the internal temperature of the colony, distribute air, and maintain its intended form. As formal complexity increases into double curved geometries, the demand of material for such moulds or formworks is significantly expensive and ultimately wasteful if the materials cannot be reused. Furthermore, to be reusable, every surface directly in contact with living substrates must be made of a non-cellulose, polymer material, to prevent the mycelium from binding to the formwork.

One of the main areas of inquiry in this study was to explore the unique capacities of mycelium composites in their intermediate stage of cultivation, when they are alive. Living mycelium biomass is heavy with water-weight, and relatively fragile. However, a unique property is that when grown in thin, fabric-like sheets, living biomass is inherently flexible – almost gelatinous – and demonstrates a capacity for significant elastic deformations. An experiment (Imhof, 2016) with mycelium composite materials grown into a sheet of natural fibre textile demonstrated this flexibility. Imhof noted that it was possible to use gravity to form double-curved geometry at this stage of the growing process, so long as the growing environment remained suitable. Beyond this preliminary test, there is a gap in the literature when it comes to refining or scaling production of forming flexible sheets of living myco-materials into complex forms. This underexplored capacity was the subject of two preliminary experiments by the MycoMatters Lab; directed by the author of this paper and assisted by student research assistants at Kansas State University. Critical to the process was a learn-by-doing approach that placed the material itself at the centre of inquiry, depended on improvisation, and fostered interdisciplinary collaboration. Knowledge and insights about the craft of growing structures were generated through *making*. Working directly with myco-materials facilitated incremental expansion of their assumed formal and performative capacities. All physical specimens described below were made by growing the mycelium of fungi from the phylum Basidiomycetes on a fiberized hemp-based substrate. The fungi were procured through Open Myco, a company in the United States that sells pre-inoculated myco-material through a license-agreement with Ecovative.

Improvised Myco-Sheet Expressions

Sheets of mycelium composite material were grown in rectangular metal baking pans roughly 300mm x 450 mm x 20mm. Against the inside of the pan, a food-safe plastic film was laid before filling with fully inoculated fibres. Another plastic film was laid across the top of the wet substrate to maintain a humid environment around the growing specimen. Before storing the pans in a warm and dark environment, the plastic film was punctured with a sterile needle to allow the sheet to breathe. With the fungal species being used in this application, it typically took four to five days for the mycelium to bind the hemp fibres. In this stage myco-sheets were flexible, heavy with water weight and fragile. The two layers of plastic film thus served to provide reinforcement to the living myco-sheet while it was being removed the from the pan and while it was being actively bent and manipulated. A technique developed through iterative material improvisations demonstrates how local bending capacities, reinforced with plastic film can be leveraged to shape sheets in self-standing curved forms. Most specimens made in this phase of research were based on a self-supporting interaction of two actively bent sheets. Clamps, hemp twine, and wood dowels held together, actively bent, and stabilized sheets in curved configurations for several days (Figure 1), and covered in plastic film to promote myco-welding. Different iterations explored connection details between points or surfaces (Figure 2). At these points of contact the sheets grew into one another and became adhered – using mycelium as the binding glue. Critical to this process was to maintain a growing environment clean and humid to promote the mycelium to further entangle and strengthen the mycelial matrix.

Figure 1. Improvisational process for active bending and myco-welding living myco-sheets, using twine to actively introduce curvature into the myco-sheets, and clamps and plastic film were used to create a myco-welded bond between the sheets.

Figure 2. Specimens and details of the active bending myco-sheet improvisations.

Hanging Myco-Sheets

While evocative, the preliminary experiment was limited because it relied on the self-stability of myco-sheets held with connection details that did not have implied large-scale analogues. Precision in form-making was also lacking in these early specimens. As such, the subsequent experiment sought to develop a rigorous system for introducing curvature to myco-sheets.

Shell structures gain their strength and stability through their curvature. Calculating curvature for architectural structures through a physical means has been performed for centuries by history's greatest engineers who understood that forces of gravity on flexible hanging structures can inversely generate strong curved forms of compression structures (Block et al., 2006). Among those masters, Swiss engineer Heinz Isler pioneered techniques for generating shapes of shell structures by hanging fabrics soaked in gypsum plaster (Isler, 2008). By manipulating the support conditions of the hanging sheet, different forms emerged in the fabric using gravity to generate the curvature. Left to fully dry, the rigid small-scale models could be flipped upside down to inform the design of a shell structure in compression. With the goal of developing methods for reducing or eliminating the need for excessive demands of formwork in myco-fabrication, researchers in the MycoMatters Lab adapted Isler's gravity hang-dry method as a framework for introducing curvature to myco-sheets in a precise and repeatable manner. The requirement for a myco-structure to hang is a radical departure from previous literature, which assumes the material works only in compression. The technique proposed here assumes that living myco-materials have *some* resistance to local bending and tension stresses. While this is something which could be quantified, it does not fall within the scope of the research presented here. Another assumption is the technique only informs about properties of living mycelium composite materials at this scale – understanding the technique may not be entirely scalable. As such, the lightweight double-curved shell structures produced with the gravity hang-dry method were designed as units that could be aggregated and arranged in myriad ways.

A systematic method was devised to grow composite myco-sheets (Figure 3) where approximately 20mm of inoculated substrate was spread in a chamfered square form (450mm x 450mm). The chamfered edges were made thicker to provide resistance to local stresses from hanging at the supports. The sheets were grown on tables covered in a reusable plastic tarp, which folded over to provide the proper dark, clean, and humid environment. A hanging apparatus was made from a wood frame with a stretched metal mesh. Once sufficiently grown, the sheets were hung from the apparatus with natural yarn and twine. A post-tensioning system to finely adjust the distance between each hanging point, made it easier to control the global form of each sheet. Left for several days, the sheets dried in their double curved vault forms. The lightweight modules were later dry-stacked in alternating rows, making a screen wall structure (Figure 4). Though not load-bearing, such screens could be combined with other more massive myco-structures to develop a hierarchical myco-structure system. Eliminating growing moulds completely caused a degree of uncertainty about the thickness and density of the substrate. Variations in mycelium and substrate densities caused by environmental variations in the grow space, yielded different natural hanging forms for each sheet. Other significant variables included the position of hanging points on the corners of the sheets and the attachment points on the grid of the hanging apparatus. Due to a lack of guidance systems, such as augmented reality-assisted fabrication, there was variation in the curvature and form of each sheet.

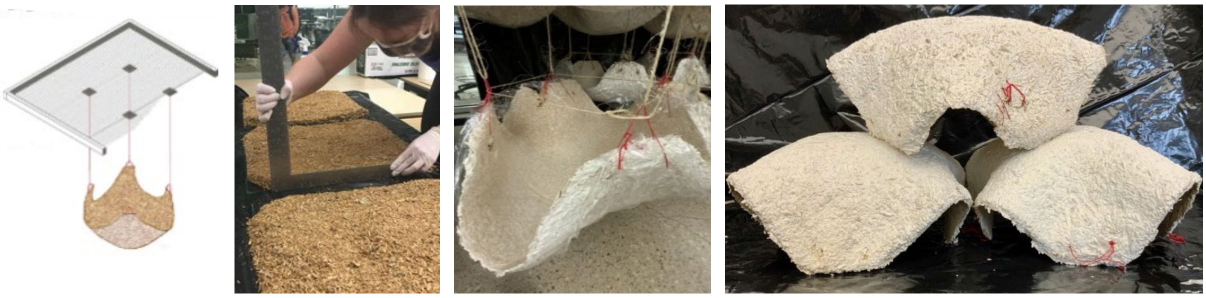

Figure 3. From left to right: process diagram for the hang-dry method, laying out substrate, gravity-forming, and preliminary stacking tests for assembling a screen wall structure.

Figure 4. Screen wall structure made with gravity-formed mycelium composite material sheets. The individual units were grown and formed in the MycoMatters Lab by Ann Lomshek and Nicole Reimert Burró, students at Kansas State University.

MYCO-SHEET PROTOTYPES IN COMPRESSION AND TENSION

The processes and accomplishments of the experiments detailed above proved it was possible to leverage the inherent flexible material properties of living myco-materials to grow expressive and previously un-predictable structural forms with novel hang-dry methods. Such forms would be otherwise not possible or inefficient using typical casting, or formwork-based approaches. The results of these experimental studies led to the development of the unique fabrication tactics proposed here, which generate curvature in flat myco-sheets by hanging and drying the living specimens from pre-defined support points, without the need for wasteful formwork. Two novel prototype structures are outlined in the following subsections, which build on and scale-up the hang-dry techniques by incorporating common and widely accessible photogrammetry and augmented reality technologies to gain a level of precision and accuracy. The first structure is a three-dimensional catenary arch grown from a single flat sheet. The second structure is a hanging shading and filtering structure made of a swirling array of four 1.5 metre-long myco sheets.

All myco-sheets for these prototypes were grown on tables between two layers of reusable black plastic tarp and a layer of plastic film which maintained a humid environment for the specimens, blocked light, and provided an extra layer of protection from contaminants. The work was done in a room that had minimal airflow. After letting the sheets grow for one-week, sterilized hemp twine was hand-sewn at pre-determined hanging points that best distributed the local stresses from hanging across the entire sheet. Following intuitions developed in the first experiment, the twine was left to entangle into the mycelial matrix. During the bending process, the plastic film on the exterior surface of the sheets was kept and provided additional tensile reinforcement to counter imposed bending forces. Due to their size and number of hanging points, at least two people were needed to hang and form the myco-sheets. A level of control and precision was sought through the open-source, smart-phone based augmented reality (AR) app Fologram. Curves generated in Grasshopper were projected in AR to each myco-fabricator's smartphone so they could follow the digital model while forming a myco-sheet. Guided by this digital overlay, precise adjustments to global curvature could be made by repositioning hanging points and adjusting the lengths of twine. After hanging the sheets into their predetermined form, plastic film on each sheet was removed and disposed of. Within three days of air drying the myco sheets were mostly dry, rigid, and much lighter.

The Unrolled Myco-Arch

This prototype intended to validate that the hang-dry method could be implemented at larger scale and grow a load-bearing compression structure from a myco-sheet. The form of a double-curved catenary arch was generated in Rhino/Grasshopper using a particle spring-simulator (Kangaroo 3d) and verified using graphic graphical analysis methods, as shown in Figure 5. The three-dimensional form spans 1.4m and stood about 80 cm tall; serving as the target geometry for the prototype. It was generated such that it could be flattened [unrolled] and grown as a myco-sheet. The curves were intentionally simple and designed to be achieved with flexible, re-usable formwork materials that could also be sanitized prior to packing with inoculated hemp substrate. As shown in Figure 6, flexible acrylic strips (6mm thick) were actively bent to form the outer walls of the unrolled arch against a long table covered in a plastic tarp. Approximately 10 kg of wet inoculated substrate was spread across the table with a gradating thickness of 25mm at the centre of the sheet and 50mm at each end. In contrast to the small-scale gravity formed units in the previous section, the arch in this experiment was formed on its side. Using gravity to find the shape of the arch would have likely been more accurate, but such a technique has its limits in scale. Flipping large catenary structures from hanging to standing imposes eccentric loads that risk prematurely damaging them without significant reinforcements. Hanging the arch on its side permitted it to be lowered from the hanging apparatus and tilted up after drying. Five hanging points were sewn into the myco-sheet. The sheet was formed with the assistance of Fologram, projected in AR to each myco-fabricator's smartphone. The focus was achieving the correct arch form in section, but due to limitations of the smartphone-based interface and uncertainty in the capacity of the material to withstand drastic curves without tearing, only some double curvature at the arch footings was imposed. Fully dried the arch weighed 3.5kg and the thickness had reduced to roughly 20mm at the peak. Figure 7 shows the unrolled myco-arch supporting a concentrated load of 31kg at its peak before failing.

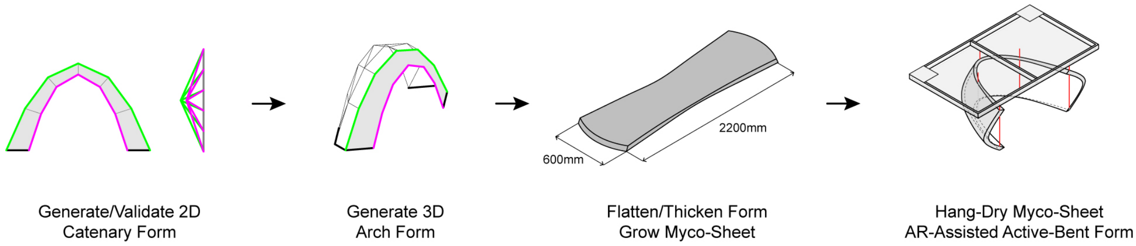

Figure 5. Process diagram for designing, cultivating, and forming the unrolled myco-arch.

Figure 6. Forming process of myco-materials from loose inoculated hemp substrate (right) to working with smartphone-based augmented reality to register the arch form into the myco-sheet.

Figure 7. Testing the Unrolled Myco-Arch to failure. The arch, which weighed 3.5 kg held a concentrated load of 31 kg before collapsing.

The Hanging Myco-Chandelier
The growing interest in myco-materials in the architecture and engineering communities led to a lively collaboration between engineers and computational designers at Silman and the MycoMatters Lab. The focus of the collaboration was to address the critical gap of knowledge in building science and design that pertains to the broader deployment of myco-materials in the context of residential architecture. The team collaborated on a speculative residential commission to renovate a conservatory space with a custom structure that would perform as a hanging sunshade, absorb sound, and made entirely out of myco-materials. Computational models were developed for shading structures, that responded to the design criteria. Among those developed by Omid Oliyan at Silman, a family of designs consisted of sheets twisting from vertical around the center to horizontal around the edges. *The Phoenix* (Figure 8), became the source of inspiration a physical prototype that sought to further exercise the hang-drying method, while expanding the context for applications of the structures that are made possible by bending myco-sheets.

Four composite myco-sheets 300mm x 1500mm x 35mm were each grown from roughly 6.5kg of inoculated hemp fibres and formed with a prefabricated frame. The sheets were grown two at a time, over several weeks. A similar table-top method previously described was used to grow the sheets including the use of twine at the hanging points, which also were let to be incorporated into the material matrix. The forms introduced to the first two sheets through active bending were improvised. The process involved working with the hang-drying method visually and intuitively; ensuring no tearing in the mycelial polymer matrix; to determine how much curvature could be introduced. This was done with the understanding that if a tear should occur, living biomass has the capacity to self-repair. Once the bend was achieved, the hemp twine was adjusted to further control the form at the hanging points. After the sheets dried, they were scanned (Figure 9) using an open-source photogrammetry software called Meshroom (AliceVision, 2021). These scans were used to further develop a design based on the curvature of the two improvised sheets using a custom workflow in Rhino/Grasshopper. When the second pair of myco-sheets were sufficiently grown, they were hung in a similar manner – this time guided by smartphone-based augmented reality to impose the pre-designed curves into the sheets (Figure 9). Limiting the complexity of the target geometry by-design made it more feasible to approximate the alignment of the myco-sheets with digital curves projected to the myco-fabricators' smartphones. In bending all four sheets, the plastic film, which was used in the initial growing stages to further isolate the growing sheets, also provided tensile reinforcement to counter imposed bending forces. Once all four curving sheets were dried, they were assembled with an augmented reality guided process into the hanging prototype structure called *Myco-Chandelier*.

Figure 8. From left to right: The Phoenix design concept by Omid Oliyan; growing a myco-sheet; forming large mycelium sheets by hanging only - improvisational method.

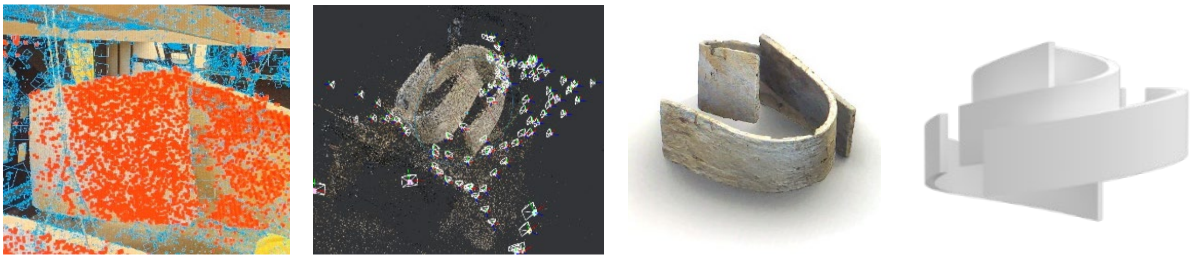

Figure 9. From left to right: scanning process of hanging sheets and screenshots from Meshroom; Digital model of the myco-chandelier.

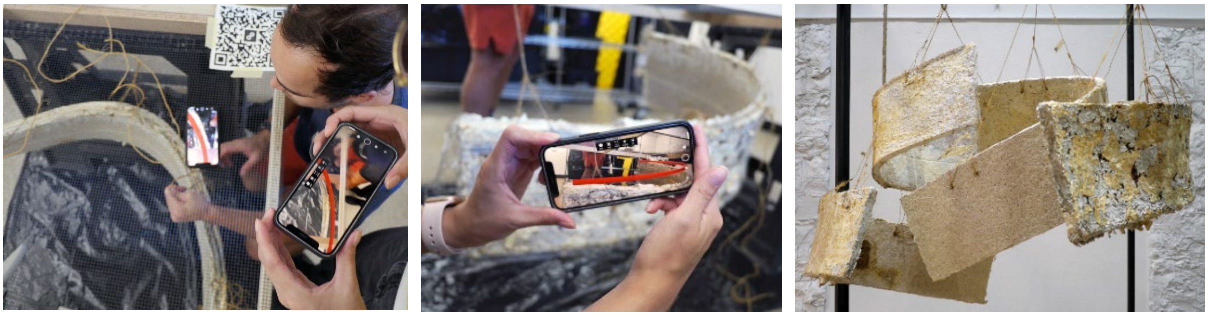
Figure 10. The myco-chandelier formed through improvisations, and computational responses.

DISCUSSION AND FUTURE WORK

The novel fabrication methods proposed here leverage the flexible nature of living sheets of myco-materials to generate curvature by hanging and drying living specimens from pre-defined support points, without the need for wasteful formwork. Such complex curves are otherwise inefficient, if not impossible, using common form-packing, casting, or other formwork-based approaches. With the material itself at the centre of inquiry, insights on the craft of growing myco-structures developed were never assumed, always generated through making, and shared between collaborators. The improvisational learn-by-doing approach to myco-fabrication led to computationally generated design proposals that were in radical contrast to the heaviness of previous myco-structures that assumed the material works only in compression. While this paper focused on scaling up the sheet growing and bending methods, the improvised sheet expressions also demonstrated small-scale myco-welding of sheets that will be introduced in future iterations of this work. Together, the screen wall made of gravity formed sheets, the compression-bearing Unrolled Myco-Arch, and the hanging Myco-Chandelier prototypes challenge previous assumptions about the formal and structural capacities of myco-materials, and highlight that *at this scale*, living myco-materials are sufficiently strong to be *self-supportive in tension*.

The benefits of the proposed fabrication methods are accompanied with consequent design constraints. Most significant is the requirement for design modules to be made from developable surfaces; that they can be fabricated from flat sheets. Another constraint relates to the maximum allowable curvature in the hanging sheets, such that the myco-material does not tear or break. This maximum curvature is governed by the sheet thickness and mechanical properties of the living specimen and needs to be determined experimentally. The accuracy of the curves achieved through bending and hanging, and the extent to which those techniques were scalable were other notable limitations. Incorporating improvisation, 3D-scanning with photogrammetry, and augmented reality-guided fabrication, were vital to achieving the goal of forming living myco-sheets into complex and double-curved forms through hanging and active bending. Future work should work should continue to find cooperative logics between fungal growth, computational design, and digital fabrication to expand upon existing formal, structural, and constructive paradigms of myco-materials. The ability to grow twine and other natural-fibre textiles into the material matrix suggests that through computational design and analysis, strategic placement of such reinforcements could be deployed to selectively strengthen and enhance myco-materials. Robotic fibre winding and CNC knitting are two fabrication technologies that have been widely demonstrated and could be immediately applied in the context of myco-fabrication. The raising popularity of “co-bots” also suggest a future in which machines could collaborate with craftsmen and carry out improvisational tactics with greater precision, reduced demand for labour, and potentially much safer and cleaner fabrication conditions.

Radical approaches to sustainability also raise questions of material ethics when evaluating what and how much was wasted in different approaches to myco-fabrication. Although myco-materials are widely known to require far less energy to extract and manufacture compared to the petro-chemical foams and plastics, there are critical ethical questions that must be considered – particularly in the near ubiquitous use of plastic in myco-fabrication. In the context of the experiments presented in this paper, plastic sheeting and film played significant roles in maintaining a proper growing environment for the mycelium and keeping away contaminations. These plastics were needed because the myco-sheets were produced in an environment could only be partially controlled. Plastic film was used ubiquitously to cover living substrate and contain the humidity of hemp fibres in close contact. The tables were covered in a reusable plastic tarp, which folded over to provide the proper clean, humid, and dark environment. Even in the context of forming myco-materials through hanging, which eliminate all plastics for shaping, plastics are still not avoidable – though significantly less.

CONCLUSIONS AND FUTURE WORK

There is an urgent need for low-energy and renewable building materials that divert building and demolition waste from landfills and lessen the impact of the construction industry on climate change. At a time when buildings have shorter-than-expected lifespans that result in landfill disposal, myco-materials help challenge a traditional notion that ties permanent building materials with the permanence of building structures. While myco-materials have inherent structural, isolative, and fire-resistant properties that suggest it is possible, no integrated building system has yet been invented to grow and assemble an entire house out of mycelium. This paper has taken a critical approach to applications of myco-materials used for large scale structural design applications, which have previously lacked in diversity, due to the critical gap in scientific knowledge that pertains to the deployment of myco-materials in a manner other than brick/block, monolithic casting, or 3D printing-based approaches. As a response, the novel method in myco-fabrication proposed here generates complex curvature in flat myco-sheets that are otherwise not possible or inefficient using common form-packing, casting, or formwork-based approaches. The experiments and prototypes presented here ultimately outline a framework for scaling a new material technology in ways relevant to architecture, engineering, and construction industries.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY

Data on which this paper is based is available from the authors upon reasonable request.