In Pursuit of a Grown Environment:

Material-Driven Design Exploration of Mycelium-Based Composites for Consumer Product Applications

Avery K. Gendell

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Jonas Hauptman, Chair

Brook Kennedy

David Dugas

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Abstract

Many human-created systems of production, consumption, construction, and infrastructure–known as the built environment–have had detrimental effects on the natural world and human health alike Ellen MacArthur Foundation, 2022; Siddiqua et al., 2022). Consequently, such systems must be rethought with a focus on restoring and protecting the health of the planet and its inhabitants. This thesis seeks to demonstrate the viability of using highly sustainable mycelium-based composites (MBCs) to replace unsustainable materials across multiple consumer product applications by responding to the question, "How can design help realize a grown environment?" A "grown environment," in the scope of this work, is a philosophy that pursues symbiotic relationships between humans and the planet by prioritizing waste elimination and ecological preservation. Despite the recent acceleration of MBC research and growing consumer desire for environmental sustainability, user perceptions of MBCs remain hesitant due to their generally distinctive and organic appearance (Bonenberg et al., 2023).

Additionally, while significant work has been done to research the relationships between fabrication variables and material performance of MBCs, MBC research is deficient regarding applied contexts of these fabricated materials. Most research currently available is experimental with a focus on defining relationships between material properties isolated in an abstract setting. Some contextual efforts do exist, but generally remain low-to-medium fidelity and lack quantitative justification or support.

Responding to this gap, this thesis utilized a material-driven design (MDD) process to produce maturely designed mycelium-based consumer products (CPs). Investigation was completed in three main stages: 1) abstract MBC production experimentation, 2) semi-applied MBC design and production, and 3) applied MBC design and production. This strategy created a dialogical, iterative relationship between the design and material, allowing it to manifest appropriately into its final applications. The outcome of the thesis is a body of work comprised of material samples and product prototypes that demonstrate the ability of MBCs to effectively respond to the complex material demands of consumer products while respecting the value, strengths, and agency of the material.

The broader contribution of this work is in the novelty and relevance of its scope. By combining evidence-based material knowledge with applied design studies, this thesis bridges components of desirability, viability, and sustainability that are critical in demonstrating the potential of MBCs for consumer product applications.

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General Audience Abstract

This thesis seeks to demonstrate the potential of mycelium-based composites (MBCs) to replace unsustainable materials in consumer products. Mycelium composites are sustainable and renewable materials made by growing the root-like body of mushrooms (mycelium) on organic materials like sawdust, soybean hulls, and hemp. Existing research has shown that properties of MBCs like strength, density, hardness, and flexibility, can be tailored to certain needs, depending on how they are produced. Many materials used in consumer products, like plastics, fiberboard, foam, and more are non-renewable, non-recyclable, and hazardous to human and environmental health. Since MBCs can adopt many similar traits to these materials, they can potentially offer the design industry a highly sustainable material alternative. However, despite the need for increased sustainable production, increasing consumer desirability of sustainable materials, and the growing body of MBC research, the material faces obstacles to adoption.

Research has demonstrated that consumers remain hesitant of MBCs due to the material's generally distinctive and organic appearance. Additionally, a large gap in MBC research exists regarding applied contexts. Most experimental research creates small material samples and tests them on specific properties like tensile and compression strength, but little research applies the same rigor to applied use cases of MBCs. Some contextual efforts do exist but often are low-to-medium fidelity or lack quantitative justification or support. Responding to this gap, this thesis utilizes a material-driven design process to produce maturely designed consumer products from mycelium-based composites in an effort to demonstrate the material's rich and growing potential.

To my family,
for their unwavering support, acceptance, and encouragement.

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BioDesign Research Group

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Introduction

Dire Need

The planet is facing a growing climate crisis, and the design industry plays a significant role in creating ecological turmoil. Many products create extensive material waste during manufacturing and some products have designed obsolescence, artificially limiting their useful life span, sending them to landfills hastily (McDonough and Braungart, 2002, p. 27-28). Furthermore, “monstrous hybrids” are products and materials that irreversibly bind “technical and biological materials” to one another, destroying potential routes of recycling, reuse, or biodegradation (McDonough and Braungart, 2002, p. 99).

In addition to waste and its impact, products are responsible for significant greenhouse gas (GHG) emissions. One study found that 65% of yearly global carbon dioxide emissions are attributed to households, and within households, 17% of CO2 emissions are embodied in purchased manufactured products (Ivanova et al., 2016). This means that roughly 10% of CO2 emitted worldwide can be attributed to consumer products. Another study revealed that on average, a product embodies 6 times its own weight in carbon emissions (Meinrenken et al., 2020).


via Renamarie for Shutterstock

10 million tons of furniture were landfilled in the US in 2018.

(US EPA, 2018)


via DimaBerlin for Shutterstock

17% of a household’s carbon footprint comes from manufactured products.[3]

(Ivanova et al., 2016)

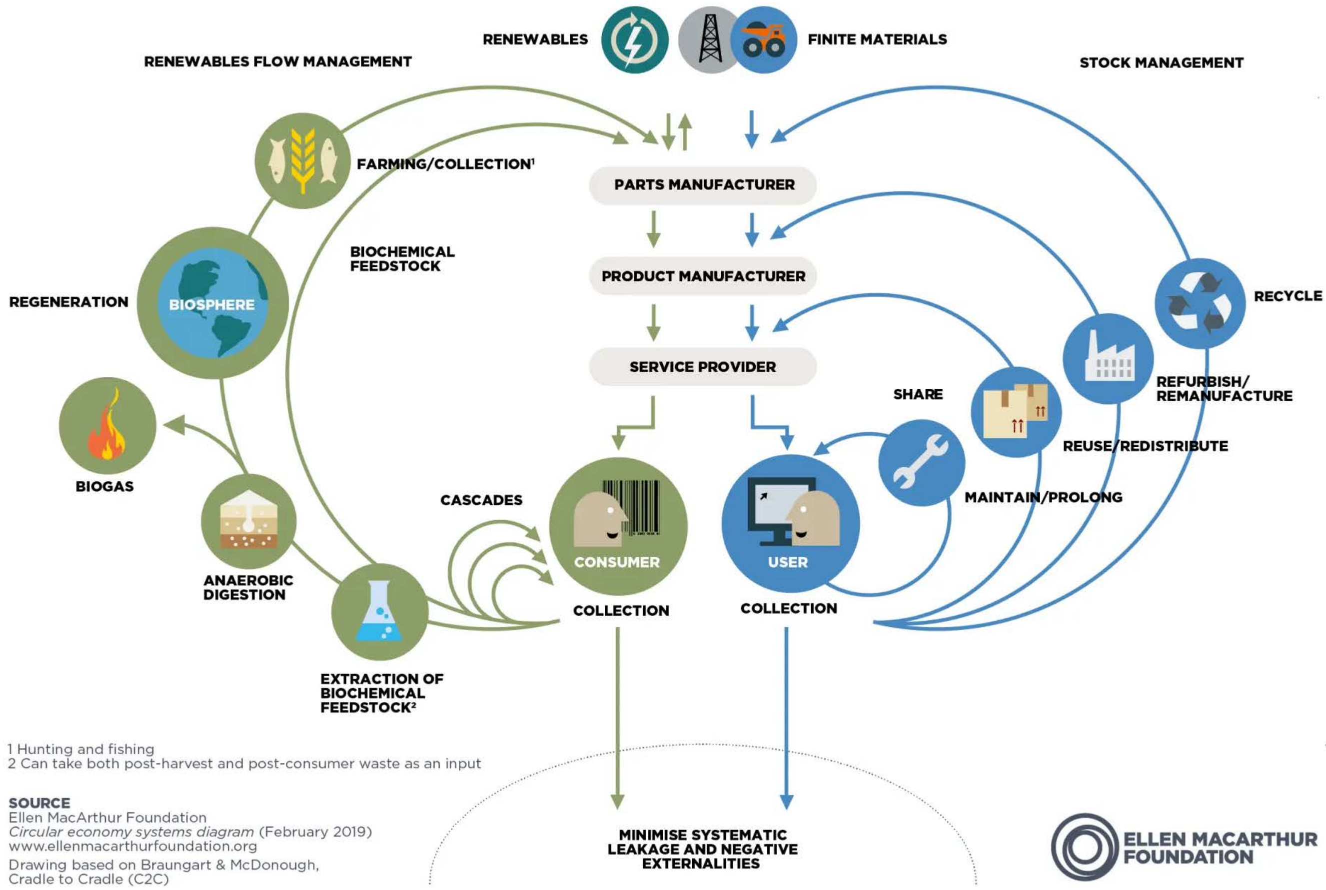


Figure 1: Circular Economy Systems Diagram, Ellen MacArthur Foundation, 2019). The "butterfly" diagram depicts the biosphere (left) and techosphere (right) material and product loops.

Circular Economy

Transitioning from a linear economy, where materials are extracted, transformed into products, used, and ultimately discarded or downcycled, to a circular economy (CE) where materials and products are reused and transformed rather than discarded, is critical in sustaining both human and environmental health (Ellen MacArthur Foundation, 2023). Linear economies are ubiquitous and domineering today but they are a recent phenomenon. In broader ecological and human contexts "what we call circularity has historically been the rule, rather than the exception" (Liden, 2023, p. 12); in nature, "there is no such thing as waste" (McDonough and Braungart, 2002, p. 92).

Design plays a critical role in transitioning to a CE. The three fundamental principles of the CE are "eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature" (Ellen MacArthur Foundation, n.d.). The CE categorizes materials and products into either the biological or technical cycle. The biological cycle deals with renewable "materials that can biodegrade and safely return to the earth" while the technical cycle deals with products and materials that are "used rather than consumed" and comprised largely of non-renewable resources (Ellen Macarthur Foundation, 2022).

Consumer products are considered technical elements, even if they are made of biodegradable materials. Such biodegradable products, however, are made from materials that originate in the biological cycle and have the capacity to return to it at the end of their lives. Thoughtful design that prioritizes CE principles can create systems, products, and services that are mutually beneficial for humans, the built environment, and the natural world. In respect to product design, methods of "maintenance, reuse, refurbishment, remanufacture, recycling, [or] composting," must be built into a product's lifecycle (Ellen MacArthur Foundation, 2022).

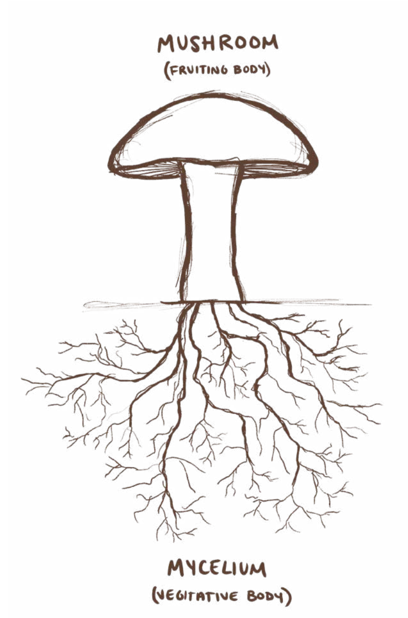
Two important facets of a product's environmental impact are its end of life treatments and its carbon footprint. A product's end of life (EOL) refers to what can and will happen to a product after it is no longer useful. The design of the product dictates what is possible at its EOL and what impacts it has (Ellen MacArthur Foundation, 2022). If a product is comprised of both technical and biological components, can those materials be separated or are they permanently bound? Many products are destined for landfills, destroying any remaining value of its trapped technical or biological materials. Landfills pose a treat to human and environmental health; they emit greenhouse gases and carcinogens and pollute the air and groundwater (Siddiqua et al., 2022). Repairability and maintainability also play roles in a product's EOL; the longer a product's useful life, the less proportionately impactful its EOL is.

A product's carbon footprint discusses the global warming potential (GWP) it possesses. Despite its name, a carbon footprint generally accounts for the effects of all greenhouse gases (GHGs), not just carbon dioxide. The GWP measures "how much heat different GHGs trap in the atmosphere" (Liden, 2023, p. 12). Measured in CO2 equivalent (CO2e), if a product's GWP is 1 kg CO2e, its existence resulted in GHG emissions equivalent to those emitted by the average passenger vehicle every 2.5 miles of driving (US EPA, 2016). All stages of a product's life, from the resources and energy that go into material cultivation, extraction, and processing, to product manufacturing, transportation, distribution, and use are contributors to its GWP.

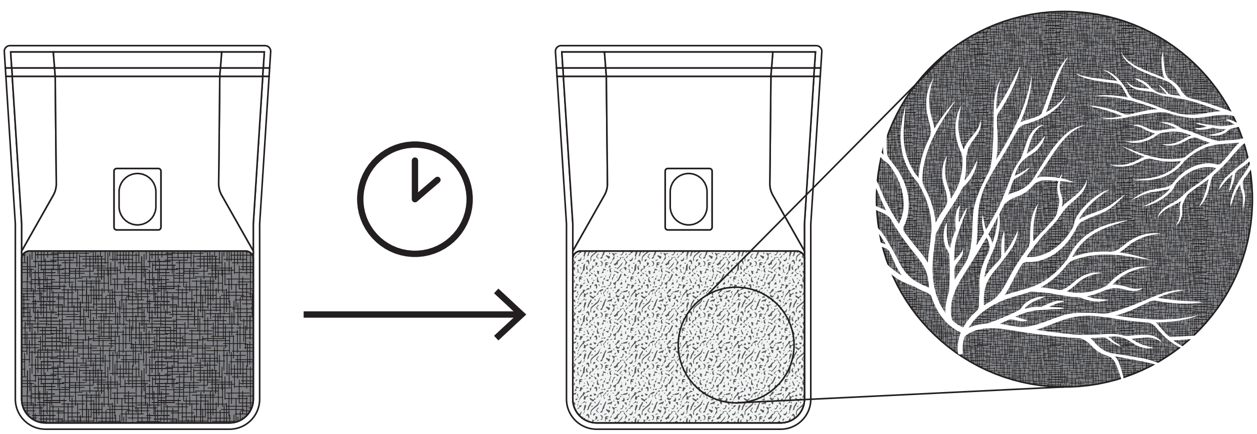
Carbon footprints, or global warming potential, and end-of-life are not the only variables of a product's environmental impact, nor is environmental impact the only important criteria. Resource exploitation, material renewability, recyclability, and toxicity, labor ethics, and more are also critical factors to consider.

Mycelium-Based Composites

Mycelium is the root-like vegetative body of fungi. Comprised of a network of fine, hair-like hyphae that excrete digestive enzymes, the mycelium is responsible for conducting the external digestive processes the fungus needs to live, but often it does much more than that. In nature mycelium lives predominantly underground and as it grows, creates mycorrhizal networks that connect the roots of trees and other plants. These networks, sometimes referred to as the “wood wide web,” often facilitate the health of ecosystems by enabling plants to communicate and share resources (Mycorrhizal Fungi Explainer and Definition, n.d.).



In the built environment, mycelium can be grown on organic materials rich in lignin and cellulose to create natural composite materials, or mycelium-based composites (MBCs). As the mycelium digests its substrate–the materials on which it’s grown–it forms an intricate 3-dimensional network, binding the substrate aggregate together. MBCs can be molded into a wide variety of shapes and sizes for many applications. The most common uses of MBCs in industry are packaging and insulation, but are also used in lighting, furniture, and other products.



The Case for Mycelium-Based Composites

The demand for sustainable products is rapidly accelerating, from both environmental conservation, and consumer desirability perspectives (Bonenberg et al., 2023).

Mycelium-based composites (MBCs) offer the design and architectural industries a sustainable material alternative to common materials like foams, insulation, wood-like composites, and others which are produced at significant scales and are largely non-renewable and non-recyclable (Meyer et al., 2020; Appels et al., 2019; Houette et al., 2022). These materials follow a linear economic model, where their lives follow a straight trajectory from material extraction and product manufacturing to use then disposal, often in landfills (Ellen MacArthur Foundation, 2023). MBCs, however, fit excellently within a circular economy model as they can upcycle waste materials and fully compost, cleanly reentering the biosphere (Meyer et al., 2020). MBCs are made by growing fungal mycelium, the vegetative root-like body of fungi on organic substrates that are rich in lignin and cellulose. The mycelium, composed of a growing three-dimensional network of hair-like hyphae, partially digests lignocellulosic substrates such as wood chips, soybean hulls, and hemp fibers through extracellular digestion, consequently binding together the substrate particles, resulting in a final cohesive composite (Houette et al., 2022). A shift towards sustainable materials that can work within the circular economy like MBCs is necessary to reduce waste, pollution, and overconsumption of non-renewable materials in an ever-growing world (Houette et al., 2022). As will be discussed further, many material properties of mycelium such as density, elasticity, strength, and stiffness can be predictably tuned during production by altering fabrication processes like substrate composition, particle size, compression, heat treatment, and more (Appels et al., 2019; Elsacker et al., 2019; Houette et al., 2022).

Obstacles to Adoption

Despite their physical and mechanical material potential, consumer acceptance of MBCs is low, largely due to their aesthetic manifestations (Bonenberg et al., 2023). Moreover, research into aesthetic optimization and applied uses of MBCs for consumer products is sparse. A small number of mycelium-based consumer products are currently on the market, and MBC material property research has provided mature conclusions on its physical potential, but little work effectively marries the abstract research with applied uses. Furthermore, no known research explores the optimization of MBC desirability alongside functionality.

Approach

In Pursuit of Sustainability

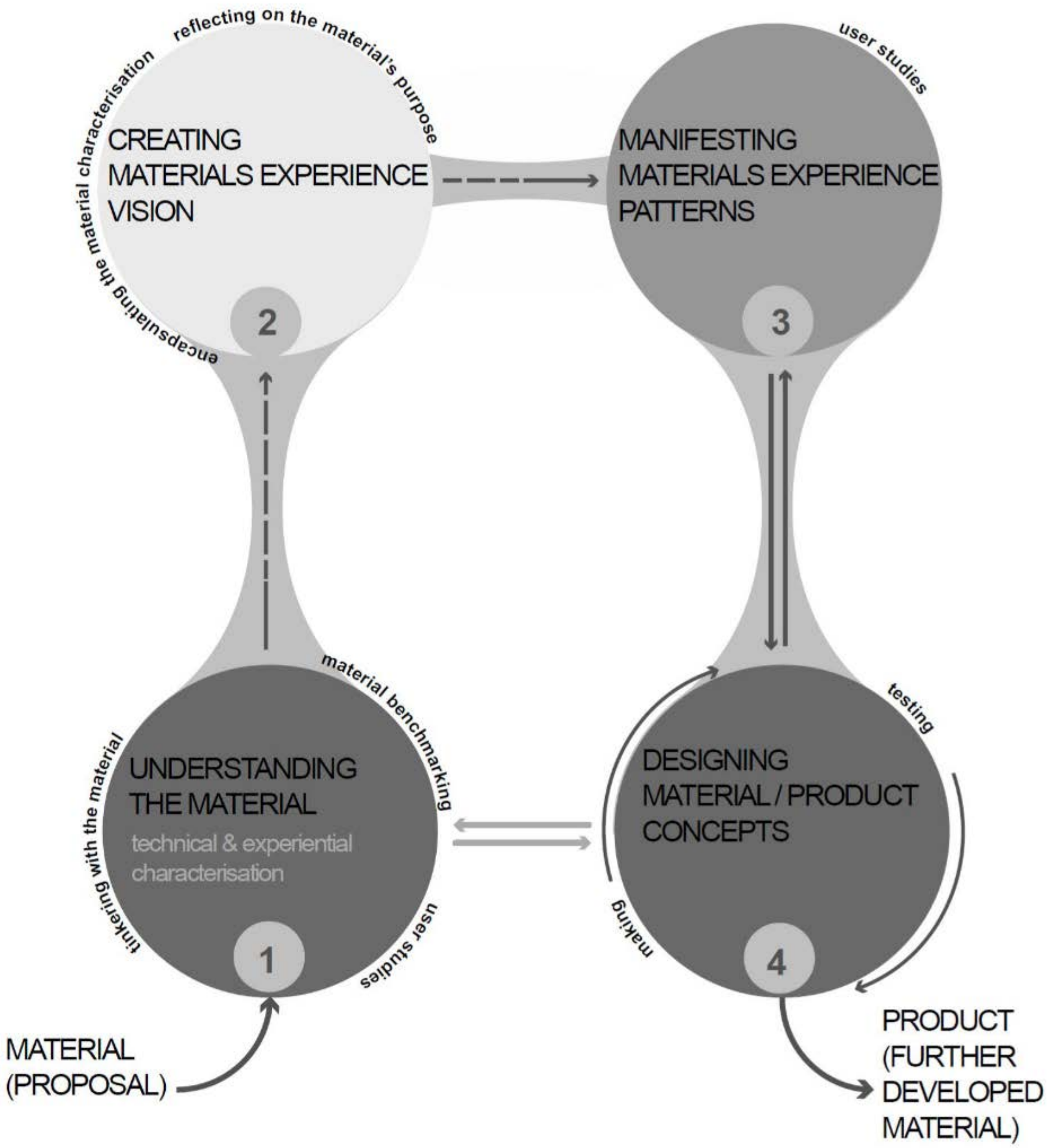
From the highest level, this thesis seeks a sustainable, healthy future for the globe and its inhabitants. This future is threatened by the contemporary climate crisis and its causes, one being the global reliance on unsustainable materials used in consumer products (Ellen MacArthur Foundation, 2023). At a tangible level, this research will use a material-driven design approach with a novel scope to produce a high-fidelity consumer product from MBCs based on practical and theoretical design and fabrication strategies.

Beginning with abstract MBC production experimentation, the research will explore the effects of MBC production and processing on the final material properties, namely, material perception and material performance. In this context, material perception categorizes the aspects of the composite that influence the material semantics and connotations to users like color, scent, texture, and others. Material performance refers to the mechanical behaviors of the final composites, like hardness and strength.

This first stage will provide heightened material understanding and "materials experience vision," the critical first step in a MDD process (Karana et al., 2018). The second stage will build on data-driven results from stage 1, beginning to bridge the gap between abstract and applied settings. The third and final stage seeks to produce at least two mature mycelium-based consumer products that demonstrate an impressive range of elevated applications for MBCs. Using a seat and luminary as case studies, the final prototypes will showcase MBC's potential strength, durability, visual desirability, and applied performance.

A major goal of this thesis is to encourage designers, architects, and scholars at large to embrace the potential that MBCs possess to replace plastics and unsustainable composites in consumer product industries and lighten the industry's global environmental impact.

Material-Driven Design



Material-driven design "qualifies the material not only for what it is, but also for what it does, what it expresses to us, what it elicits from us, and what it makes us do."

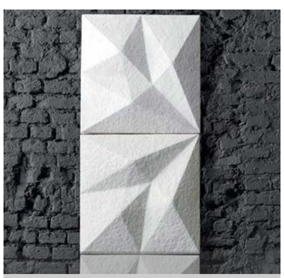
Karana et al., 2015

Front Stage / Back Stage

One way to categorize products and materials is by their application, more specifically the degree to which they are interacted with by users. On one hand, some products (like chairs, lamps, or decorative tiles), are regularly viewed and used by consumers. A chair is seen and sat in regularly, it must look nice and be comfortable to use. A pendant lamp must cast last appropriately and be beautiful both when off and on. For the scope of this work, these items are considered "front stage" products; their designs are driven by formal and aesthetic demands alongside functional requirements.

On the other hand, some products (like drywall insulation and packaging) have little or no ongoing interaction with the consumer or otherwise a demand for refined aesthetic expressions. Insulation, once installed, is hidden from the eye, and product packaging is discarded after unpacking. These items can be considered "back stage" products; items whose designs are driven primarily by function.

As will be discussed further in following sections, MBCs have been used in a wide range of applications that span both front and back stages, but some of the most mature and viable uses of MBCs are for back stage applications, while front stage uses are less common.

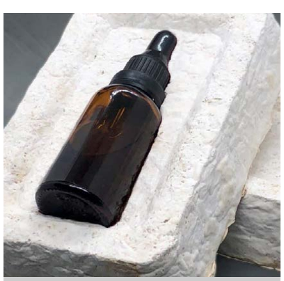

"Kite" Acoustic Tiles by Mogu


"They Grow Without Us" by AFJD design studio


Mycelium Pendant lamps by Danielle Troffe

Front stage

- Seen and interacted with
- Higher value
- Aesthetics and function-driven requirements


"Shroom Packaging" by Mushroom Material


Mycelium drywall insulation, Grown Bio by Ecovative


Wine bottle Mushroom Packaging by Ecovative

Back stage

- Low interaction
- Lower value
- Function-driven requirements

Proposed Applications

In a circular economy, sharing products is the highest priority within technical cycles, followed by maintenance, reuse or redistribution, refurbishment or remanufacturing, and recycling (Ellen MacArthur Foundation, 2022) (Figure #). MBCs are somewhat unique in their ability to span the technical and biological cycles. Once they reach the recycling loop of the CE, they can return to the biological cycle, completely biodegrade, and restore valuable nutrients and resources to the ecosystem. Considering these points simultaneously, this work proposes that MBCs can make a significant impact if they can replace materials for products that do not readily afford sharing. In other words, CPs that are fixtures in single households would benefit from full material circularity, which facilitates an additional reclamation of value, since they have little to no opportunity to cycle through the highest value loop. Consequently, furniture and lighting were established as the two case studies for this work as they fit within the seldom-shared CP scope. These case studies present disparate material demands and challenges, which, if effectively fulfilled and overcome by MBCs, will demonstrate significant breadth in MBC potential for CPs.

Sustainability Through Desirability

Responding to the identified obstacles to acceptance, research gaps, and opportunities, a refined research question was formed to further focus the research: "how can design help attune the visual and physical properties of mycelium-based composites?"

How can design help realize a grown environment? → **How can design help attune the visual and physical properties of mycelium-based composites?**

via BioMyc

Typical visual appearance of MBCs.

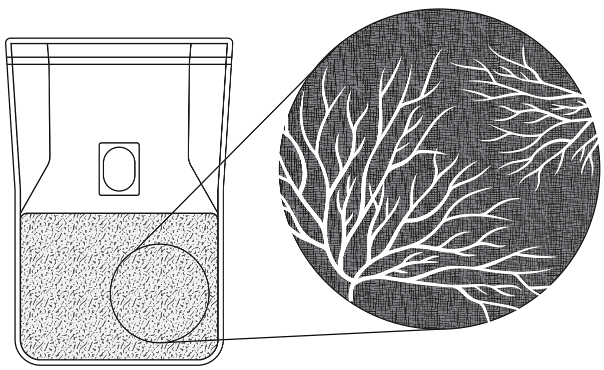
via Zeekr

Materials with connotations of high performance, precision, reliability, and luxury.

Literature Review

Scope

This literature review discusses an array of research topics that investigate MBC fabrication and objective and subjective value, alongside topics of product materiality, design, and consumer attitudes.



MBC State of the Art

Material Properties

While the material performance of MBCs in applied settings is under-researched, significant efforts have demonstrated that MBCs have tunable and desirable material properties. Physically producing MBCs is relatively simple, but there are almost endless variables that can be considered that affect the composite’s properties. This review begins with discussion of studies that explore, through a range of methodologies, the relationships between fabrication variables and material properties of MBCs. In short, these variables include fungi species, substrate composition, incubation conditions, and post-growth treatments. A more comprehensive list of variables is shown in Table 1. In all works, the potential of MBCs to serve as an effective, renewable, and viable environmentally friendly material alternative to non-renewable resources was asserted or validated.

Table 1: MBC production variables with their definitions and examples.

Category	Variables	Meaning	Examples
Fungi species	Species	The species of the fungal mycelium used	*Ganoderma Lucidum, Pleurotus Ostreatus*
	Modifications	Genetic modifications to the fungal strain	Hydrophobin gene deletion (Appels et al., 2018)
Substrate	Feedstock/fiber origin	Type of biomass/substrate material used	Sawdust, soybean hulls, shredded hemp
	Moisture content	Percentage of water in substrate	Typically, 60-70%
	Scale	Size of particulates	Small vs. large
	Geometry	Shape of particulates	Fine sawdust, coarse chips, long fibers
	Isotropy	Uniformity or non-uniformity of substrate mixture	Isotropic, anisotropic
	Orientation	Directionality of fibers	Coaxial, longitudinal, lateral
	Sterilization method	Process used to eliminate contaminants prior to incubation	Pressure sterilization, ethanol treatment, pasteurization
Inoculation	Inoculant	The type of live mycelium culture introduced to the sterile substrate	Liquid culture, grain spawn, sawdust spawn, agar plate
	Rate/ratio	Proportion of inoculant to substrate by weight	1:20, 1:5
Spawn processing	Fragmentation method	How the spawn is broken apart prior to molding	By hand, with blender, with stand mixer
	Fragmentation duration	How long the spawn is blended	1 minute, 5 minutes, 10 minutes
	Packing density	How compacted the spawn is made when packing the mold.	Low, high, measured
Mold design	Scale	Size of the molded object	
	Materiality	What the mold is made of	Plastic, wood, metal, concrete, plaster
	Volume	Volume contained within the molded object	
	Surface area	Amount of external surface area of the molded object	
	Airflow	The amount of air, whether passive or active, that reaches the molded spawn	Filtered ventilation holes built into the mold, filtered compressed air pumped through the object.
Incubation (i.e. growth)	Time	How long the molded composite is given to grow	Typically, 7-14 days
	Intra and extra mold stages	Growth periods both before and after the composite is demolded.	Typically, ~7 days in-mold, 3-7 day outside of mold
	Temperature	Ambient temperature of incubation environment	Typically, 65-80°F
	Humidity	Humidity level of incubation environment	Typically, 70-90%
	Carbon Dioxide	Level of carbon dioxide in incubation environment	High CO2, Low CO2
	Light level	Amount of light the incubating objects are exposed to	In the dark vs. in light
Post-growth processing	Compression	Amount of compression applied to the MBC after its growth period	None, 50%, 10 tons
	Heat (amount)	Temperature of heat applied to the MBC after its growth period	100°C, 200°C
	Heat (duration)	Duration of time the MBC is exposed to heat	10 minutes, 1 hour, 10 hours
Additional treatments	Machining	Subtractive processes applied to the MBC	Sanding, cutting, drilling
	Coating	Application of additional materials to the MBC	Shellac, paints, tints, dyes, UV-resistant coatings, moisture-resistant coatings.

Appels et al. (2019) explored the performance differences between two fungi species and the effect of substrate composition and post-growth processing on the final composite's properties. The white rot fungi P. Ostreatus and T. Multicolor colonized appropriately prepared rapeseed straw and cotton; and rapeseed straw and beech sawdust, respectively. After two weeks of in-mold growth and 10 days of growth outside the mold, samples were either dried, hot pressed, or cold pressed then dried; processed; and tested. Tensile strength, bending ability, thermal stability, water absorption, and moisture susceptibility tests were performed, density was measured, and hyphal density and composite homogeneity were analyzed with light and cryo scanning electron microscopy.

Analyses and test results revealed causational relationships between the processing method and material properties. Hot pressing significantly increased tensile and flexural strengths and elastic and flexural moduli. For P. Ostreatus grown on rapeseed straw samples, tensile strength increased dramatically with compression. The strengths of the unpressed sample (PRN), cold pressed sample (PRC) and hot-pressed sample (PRH) were 0.01, 0.03, and 0.24 MPa respectively. Similarly, flexural strength increased from 0.06 (PRN) to 0.21 (PRC) and 0.87 (PRH). The elastic modulus showed the most dramatic increase with hot pressing, achieving 97 MPa compared to 2 and 9 MPa when unpressed and cold pressed. Hot pressing also increased composite density by more than 3 times, while cold pressing doubled it compared to unpressed samples. Similar trends in strengths and density were shown in the P. Ostreatus grown on cotton fiber. The PRH sample demonstrated the highest density of 0.39 g/cm3, a dramatic increase from the unpressed density of 0.13 g/cm3. In comparison, medium-density fiberboard (MDF) and oriented strand board (OSB), possess densities of 0.50-1.00 and 0.55-0.70 g/cm3. Imaging analyses revealed that as both hyphal and composite density increased, so did the composite's homogeneity and strength.

Elsacker et al. (2019) investigated the effect of substrate composition on final material properties of MBCs using the white rot fungus Trametes versicolor as the mycelial matrix. Notably, all procedures and materials are comprehensively documented, offering a novel model where proprietary information does not obfuscate its replicability, as is the case with a lot of MBC research (Elsacker et al., 2019; Girometta et al., 2019). The substrate was varied both by fiber and processing type, using hemp, flax, flax waste, softwood, and straw fibers; each processed into loose, chopped, dust, pre-compressed, and tow particulate compositions. This study assessed the density, compressive stiffness, Young's modulus, moisture absorption and thermal performance of the produced MBCs. Chopped fibers were prepared with a blending and

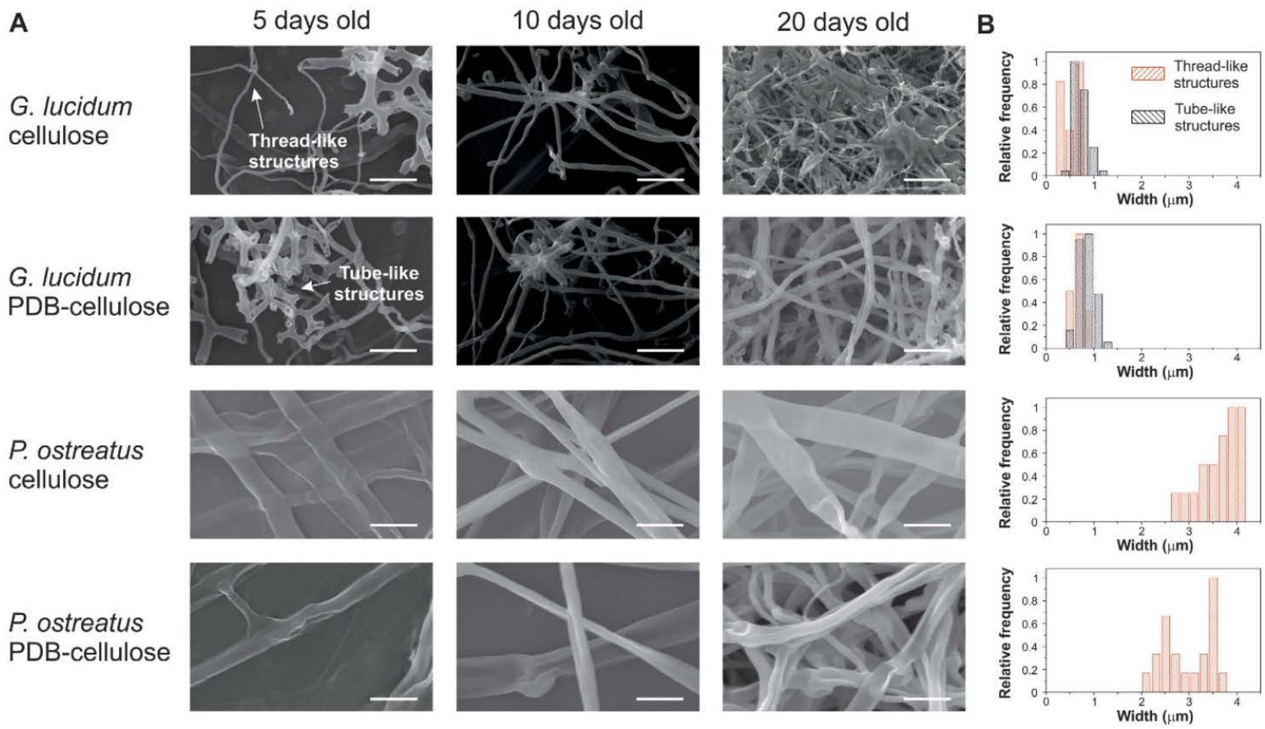


Figure 3. Morphological characterization. (**A**) SEM micrographs of *G. lucidum* and *P. ostreatus* on cellulose and PDB-cellulose substrates at 5, 10 and 20 days of growth. Scale bar: 5 μm. (**B**) histograms of widths of hyphae growth after 20 days.

Figure 1: Morphological characterization images conducted by Haneef et al., 2016.

Parameter	***Ganoderma lucidum on cellulose***	***Ganoderma lucidum on cellulose-PDB***	***Pleurotus ostreatus on cellulose***	***Pleurotus ostreatus on cellulose-PDB***	**Bacterial cellulose**	**Poly (3-hydroxybutyrate)**
Morphological description	White fibrillar films. ∼0.9 μm and ∼0.6 μm hyphae diameters.		White fibrillar films. ∼4 μm hyphae diameter.		Semi-transparent fibrillar films. 40–60 nm fiber diameter[50,53–55]	Granules. 0.2–0.5 μm diameter[56]
E (MPa)	12	4	28	17	∼9700[57]	∼3500[58]
Stress at break (MPa)	1.1	0.8	0.7	1.1	∼240[57]	∼40[58]
Elongation at break (%)	14	33	4	9	∼2.6[57]	∼6[58]
Water contact angle (°)	∼122	∼122	∼121	∼121	∼26[59]	∼89[60]
T thermal decomposition (°C)	294	293	295	295	365[61]	∼300[62]

Table 2. Summary of main properties of fungal fibers, bacterial cellulose and poly(3-hydroxybutyrate).

Figure 2: Mechanical properties reported by Haneef et al., 2016.

sieving process then dried. All fibers were then sterilized in an autoclave and four types of molds were prepared based on appropriate testing standards. Each sample was then prepared and packed into its respective mold by combining the sterilized substrate (20%) with sterile water (70%) and mycelium spawn (10%). Samples (except pre-compressed) were incubated in an air flow-controlled micro box for 8 days inside each mold and 8 days outside the molds. Compression of pre-compressed samples from 100mm to 80mm in height occurred over the second 8 days of growth (while still in their molds), then de-molded and incubated for 3 more days. Samples were then dried and tested. The samples produced densities between 0.06 and 0.19 g/cm3, with pre-compressed samples demonstrating higher densities than non-compressed samples. Results of compression testing revealed that for most fibers, there was a significant increase in stiffness with the use of chopped fibers. Hemp increased from 0.5 to 0.7 MPa, and Flax increased from 0.28 to 1.18 MPa, likely attributed to the increase in sample density. Water absorption tests revealed good moisture resistance, with average absorption rates of 0.0073-0.0147 mm/s1/2. The authors also concluded that visual assessment of the colonization level is a good indicator of compressive stiffness and water resistance, with higher levels of colonization and thicker fungal skin layers indicating better performance, respectively.

Haneef et al. (2016) used experimental methods to analyze how the addition of potato-dextrose broth (PDB) to pure amorphous cellulose substrate affected the material properties of the mycelium it nourished. The researchers grew Pleurotus Ostreatus and Ganoderma Lucidum, fungi belonging to the same white-rot group and can readily digest many of the same materials, on the two different substrates. Cellulose is the most prevalent polymer found in nature and is a good source of nutrition for fungi, while the sugars that PDB provides offer the fungi more easily digestible nutrition. After growing the mycelium for 20 days on 9.5 cm diameter disks and drying the samples, the authors used atomic force microscopy (AFM) and scanning electron microscopy (SEM) to analyze the morphology of the produced mycelium films and used ATR-FTIR spectroscopy to chemically characterize the samples as shown in Figure 1.

These images revealed that the physical structure of G. Lucidum was less affected by the difference in substrate than P. Ostreatus, while the latter experienced collapses and decreased widths of hyphae when grown on the PDB-cellulose medium. Mechanical characterization tests were also conducted to evaluate the stress-strain curves and Young's modulus of the samples. The tests revealed that both species experienced significant decreases in tensile strength and Young's moduli with the addition of PDB but increases in elongation at break as shown in Figure 2. This indicates that the less easily digestible the substrate is for the mycelium, the stiffer the resulting composite will be. Chemical analyses revealed that the PDB addition increased the proportion of lipids and proteins in G. Lucidum and P. Ostreatus, respectively, and decreased the proportion of chitin in both species. Furthermore, the authors revealed that due to morphological differences, G. Lucidum has higher fracture energy than P. Ostreatus, so its failure is more gradual. Haneef et al. (2016) also found that their samples demonstrated good hydrophobicity, echoing the findings of Elsacker et al. (2019), and their conclusions that a robust, in-tact fungal skin layer greatly improves the water resistance of MBCs.

Sydor et al. (2022) conducted a review of the state of MBC research. Most notably, they analyzed the fungi species, substrates, and relationships therebetween that were explored in MBC research between 2012-2022. They determined and justified 11 primary characteristics of fungi that most significantly contribute to the fabrication of effective MBCs. The identified characteristics are: "rapid hyphae growth, high virulence, dimitic or trimitic hyphal system, white rot decay type, high versatility in nutrition, high tolerance to a substrate, environmental parameters, susceptibility to readily controlled factors, easy to deactivate, saprophytic, non-mycotoxic, and capability to biosynthesize natural active substances" (Sydor et al., 2022).

Ridzqo et al. (2020) investigated the effects of bamboo fiber type on MBC mechanical performance. The researchers fabricated lightly compressed, non-structural boards bound by Ganoderma Lucidum mycelium that were compressed to 1/3 of their original heights. The produced boards were tested for density, swelling thickness, and internal bond. Results showed that density and internal bond strength increased as bamboo fiber size decreased (long fibers: 0.18 g/cm3, 0.0074 MPa; short fibers: 0.21 g/cm3, 0.0112 MPa; and powder: 0.23 g/cm3, 0.0248 MPa) indicating an inverse relationship between substrate size and composite mechanical performance.

Rigobello and Ayres (2022) explored the effects of substrate particle size on MBC compressive strength and anisotropic fiber-reinforced MBCs using Ganoderma Lucidum mycelium. The authors tested combinations of four levels of substrate particle size–small, medium, large, and mixed–and four levels of fiber reinforcement–no reinforcement, exterior burlap jacketing, interior perpendicular rattan fibers, and coaxial common reed fibers. They used ASTM D1037 testing standards to evaluate Young's modulus and ultimate compressive strength and FTIR spectroscopy to analyze chemical composition of the composites. Their tests found that the medium and mixture particle sizes yielded highest ultimate compressive strengths (UTS) (0.232-0.306 MPa). The coaxial reed fibers improved stiffness, with the Young's modulus of medium-sized particles increasing from 3.32 MPa (control) to 9.21 MPa (coaxial reed). Perpendicular rattan fibers weakened the UTS of the composites from 0.306 MPa (control) to 0.232 MPa (perpendicular rattan) as did coaxial burlap jacketing (0.299 MPa), but the authors suggest that jacketing may improve shear strength. Other research has demonstrated that smaller substrate particulates result in higher composite strength (Elsacker et al., 2019; Ridzqo et al., 2020). Rigobello and Ayres (2022) found this to be true between the medium (0.75-3.0 mm) and large (4.0-12.0 mm) substrate sizes, but not the smallest substrate size (0.5-1.0 mm). This is likely due to decreased airflow within the substrate. These results validate previous findings with the added caveat that scale can only be decreased to a certain threshold before weakening occurs.

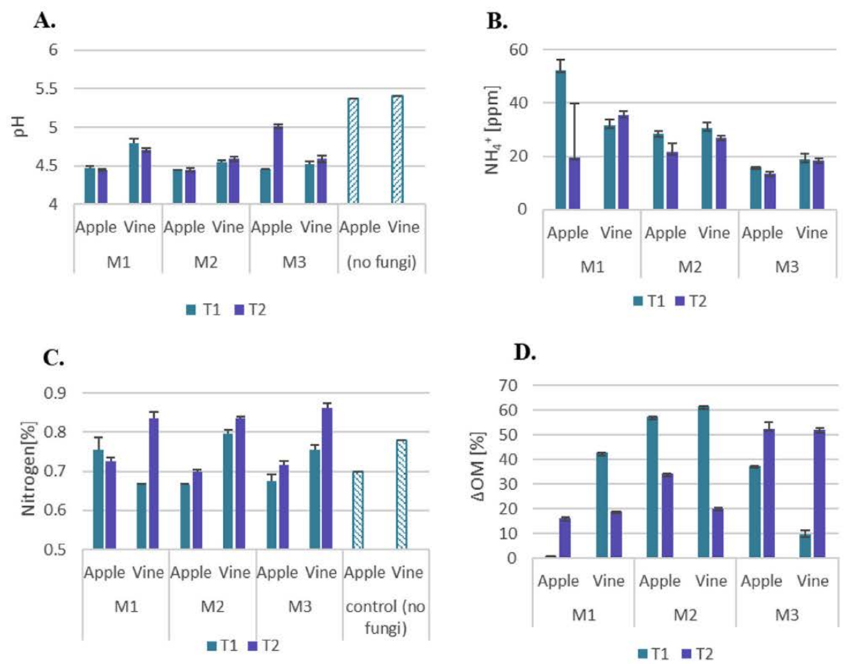


Fig. 8. Changes in chemical parameters were analyzed to evaluate and compare fungal colonization. T1 samples are in the right column and T2 in the left. These results show the effect of incubation process, substrate type, and fungi specie on: [A] pH level; [B] Ammonium (NH_4^+) content; [C] Total nitrogen content; [D] Percentage of organic matter digested.

Figure 3: Chemical changes in MBCs as reported and documented by Attias et al., 2020.

Attias et al. (2020) investigated the compression performance of MBC samples of three fungal species (Trametes versicolor [M1], Trametes ochracea (aka Trametes Multicolor) [M2], and Ganoderma sessile [M3]) grown on two varied substrates (apple [A] and vine [V] pruning waste). The effects of two varied incubation conditions (contemporary colonization and molding [T1] and molding after bag colonization and spawn fragmentation [T2]) on chemical changes were also assessed. Compression test results revealed that the vine substrate produced stronger materials (0.16 [M1], 0.25 [M2], 0.34 [M3] MPa) compared to the apple substrate (0.11 [M1], 0.15 [M2], 0.25 [M3] MPa) (values are approximated from graphs as exact values were not provided). They found that contradictory to the findings of Elsacker et al., 2019, visual colonization levels don't necessarily predict compressive strength, as the M3 samples showed lower visual colonization but highest strength. This discrepancy, however, may be attributed to the difference in species, and suggests that visual colonization level is likely an effective indicator when used in comparison to MBCs with the same fungal strain, but not across species. The authors found that incubation conditions affect MBC chemistry significantly, but very differently between species. For the two Trametes species, the percentage of organic matter digested by the mycelium was significantly higher with the T1 protocol, while the opposite was observed for the Ganoderma species as shown in Figure 3. This demonstrates that production protocols are not universally applicable between species, but process variation can successfully alter the chemical properties of MBCs.

Sàez et al. (2021) developed sandwich panels comprised of different facing materials (solid spruce wood, chipboard, MDF, and poplar plywood) bound by and sandwiching mycelium composites. Their investigation led to valuable findings about effective production processes. They found that compared to standard MBCs, sandwich MBCs require more consideration of airflow because the added faces restrict the mycelium's access to oxygen. They also found that sandwich faces made of wood composites with high amounts of glue (chipboard, MDF), cannot be successfully sterilized with just ethanol.

Consumer Perception

What aspects of a product informs consumers attitudes towards it? How does materiality affect product acceptance? What makes a product or material aesthetically pleasing? These are the questions this portion of the review seeks to answer.

A series of works that investigate relationships between products, materials, and consumer attitudes were reviewed. While scopes, specific findings, and relevance to this research varied, all reviewed work attested to the importance of context regarding product and material perception. In other words, because material demands and perceptions vary widely depending on a product's application, a material must be evaluated in the context of its use.

Karana et al., (2008) investigated the relationships between objective material properties and material desirability from the perspective of product designers. The authors place an emphasis on interpreting "intangible characteristics" of materials. These characteristics relate to the associations, meanings, and emotions that materials and their applications evoke in consumers, that are not driven fully or at all by intrinsic observable properties (Karana et al., 2008). Instead, they are driven largely by the context of the observer–their experiential and cultural backgrounds. Product designers interviewed in this work agreed that material appearance is generally the driving factor in making initial material selections. This emphasizes the idea that the more designers know about the influences on consumer aesthetic perception, the more effectively they can choose materials and design products that are appealing and desirable.

In their book, Materials and Design: The Art and Science of Material Selection in Product Design, Ashby and Johnson articulate many factors, ranging in scope from perceptual, technical, and environmental, that must be considered when selecting materials for product design. Johnson et al. (2003), and Ashby (2004) also explore this area. Very relevant to this work are the assertions that materials have both intrinsic "character" and, when applied to products, are perceived subjectively and holistically by consumers, with influences from cultural and contextual backgrounds (Ashby and Johnson, 2002, p.90; Ashby, 2004). Furthermore, despite the subjectivity surrounding consumer perspectives, there are effective methods to quantify and interpret "aesthetics," which relate to sensory properties, and "perception," which relates to symbolic and stylistic interpretation, as Johnson et al. (2003) demonstrate. The authors conducted an experiment wherein they surveyed participants about their attitudes toward products, first without, then with, the use of provided vocabulary. Their work, while not comprehensive, revealed "significant agreement" in participant associations, and the value of a provided lexicon for product interpretation.

Ashby and Johnson (2002) also highlight product/material features that are widely applicable to most contexts. For example, they attest that a "poor finish implies, however misguidedly, poor quality throughout," emphasizing the importance of surface perfection to consumers (p. 105). This suggests that surface quality is a critical metric in material design. Additionally, while they reject that "material honesty" is the only respectable approach, they iterate the need to respect the mechanical strengths and limitations of materials in product design (p.111).

In an exploratory study on "Consumer perception of bio-based products," researchers learned how participants perceive and feel about 7 different "bio-based" products (Sijtsema et al., 2016). Their work revealed that participants reacted more favorably to 100% bio-based products that have a production process that is (perceived to be) friendly to the environment and labor forces than to products that are only partially bio-based, are produced or packaged unsustainably, or conceptually misalign with sustainability concepts. Furthermore, it was found that a product being 'bio-based' is only a contributing factor to desirability if the product "looks nice" (Sijtsema et al., 2016). This finding further emphasizes the importance of visually optimizing MBCs for application in consumer products.

Another experimental study conducted by Zuo et al. (2016), investigated relationships between material texture and participants' responses to five hairdryers with differing materials and textures. In alignment with previously discussed work, the authors emphasize the importance of investigating how different material textures relate to "subjective feeling," "underlying objective [material] properties," the "context of use" (Zuo et al., 2016). Their findings indicated that product "shape, color, materials, and surface finish" have the most influence on aesthetic perceptions. Furthermore, they found that "soft, non-shiny, smooth, warm, and non-sticky" were attributes of hair dryer handles that correlated most to positive aesthetic perceptions. Since the scope of the reviewed work is very narrow (hairdryer handles), the findings on visual perceptions are more widely applicable, whereas the tactile perceptions and performance association findings are highly context specific. Of these attributes, "warmth and softness" related most to visual perceptions (Zuo et al., 2016), suggesting that these qualities may be valuable to imbue in MBCs.

Mugge et al. (2018) explore connections between product appearance and consumer perceptions of consumer durables. Through their research, the authors established five "design dimensions," "harmony, novelty, natural, weight, compressed" that provide critical and distinct indicators of "product quality, ease of use, and technological advancement" (Mugge et al. 2018). These dimensions were based on characteristic ratings of products by participants with significant design expertise. Since consumer durables carry more specific performance demands than general consumer products, this review focuses on the "product quality" perceptions as most relevant. Specifically, the authors found that products with "moderate levels of novelty" in their appearance were perceived more positively and as higher quality than those with "low or high levels [of novelty]." In addition to novelty, high amounts of harmony and moderately high levels of weight were found to positively influence perceptions of quality (Mugge et al., 2018). This indicates that material novelty, harmony, and weight may serve as effectives metric for evaluating MBC coatings and treatments.

Key Takeaways

The studies discussed demonstrated that the properties of mycelium and MBCs can be predictably varied and tuned. Both Elsacker et al. (2019) and Appels et al. (2019) showed that compression of samples increased the strength and/or stiffness of the final composite. Heat-pressing increased the density of samples across fungi species and substrate composition by more than three times while also increasing the consistency of density between samples and regulating the thickness of each sample (Appels et al., 2019). Similarly, cold pressing doubled the composite density and improved homogeneity. Furthermore, "the flexural strength increased from non-pressed to cold-pressed and hot-pressed" (Appels et al., 2019, p. 69). It was revealed by Elsacker et al. (2019) that pre-compressing samples yielded much higher Young's moduli, and by Sàez et al. (2021), that higher packing densities yield higher MBC strength.

The substrate plays a significant role in mechanical performance as well. Haneef et al. (2016) found that substrates which are less easy to digest result in higher composite stiffness, and Ridzqo et al. (2020) discovered that smaller substrate particle sizes yield higher MBC strength, except when the scale is so small, that it restricts airflow within the substrate. Furthermore, the use of internal and external reinforcement fibers and sandwich structures have the potential to significantly alter the strength properties of MBCs (Sàez et al., 2021, Ridzqo et al., 2020).

MBCs are "based on the growth of materials rather than on extraction" (Elsacker et al., 2019), a distinction from common non-renewable petroleum-derived products like plastics and foams (Appels et al., 2019). MBCs also offer many circular economy opportunities at the end of their useful lives. In addition to being fully biodegradable, MBCs can be used as fertilizer for agriculture or as a substrate on which to grow new mycelium composites (Grimm and Wösten, 2019). These renewability factors demonstrate much higher environmental sustainability than materials like synthetic foams and particle boards which generally can neither biodegrade nor be recycled. Furthermore, as was discussed above, the characteristics proposed by Sydor et al. (2022) discuss not just the desired final physical properties of MBCs, but also their orientation in industry as an economically viable material that makes positive environmental contributions. Another factor that elevates the sustainability of MBCs, especially over contemporary alternatives, is their utilization and diversion of waste streams. The substrates on which the mycelium matrix grows can and should be derived from agricultural, industrial, and post-consumer waste streams. This sequesters carbon, reduces waste, and adds economic and material value to otherwise low- or no-value streams while simultaneously reducing the production of virgin materials (Elsacker et al., 2019; Sydor et al., 2022).

The aesthetic and perceptual considerations of MBCs are critical in elevating their readiness for CP applications. The unique, organic visual condition of mycelium composites has been proposed as a desirable advantage of the material, especially as consumers are increasingly conscientious of the environmental impact of products (Sydor et al., 2022; Bonenberg et al., 2023). That said, in a study of acceptance of mycelium-based composites, despite interviewees perceiving the material as unique and eco-friendly, most still preferred the appearance of the alternative object made from a traditional ceramic material (Bonenberg et al., 2023). Such findings suggest that with research into aesthetic refinement of and education about MBCs, consumer desirability is possible, but currently immature (Bonenberg et al., 2023).

Conclusions

Extensive, but not comprehensive, research on mycelium-based composites demonstrates their material benefits, properties, and producibility while discussing aspects of readiness for CP applications. This review found that the while the environmental benefits of MBCs are clear, large research gaps exist both in bridging material performance findings from abstract to applied settings, and in the focused investigation of material aesthetics and consumer desirability. Thus, filling these gaps has the potential to expand the ability of MBCs to replace unsustainable materials at a greater scale, positively impacting the world at-large.

Design and Industry Precedents

Over the last 2 decades, a number of designers, artists, and architects have explored mycelium-based composites. These existing efforts, while limited, range in scale from architectural structures to furniture and handheld products.

The most common and mature use of MBCs in products is for packaging applications. Mushroom Packaging, by Ecovative, a United State-based company sells both custom and ready made protective packaging from MBCs. Mushroom Materials, a New Zealand-based startup also sells mycelium-based packaging. Insulation is also a common application, both thermal and acoustic. Mogu, an Italian company sells mycelium-based acoustic tiles and panel systems.

In terms of consumer products, designer Phil Ross creates and sells mycelium and wood furniture, and was one of the first to do so. Ecovative has produced multiple mycelium-based furniture pieces, but none are currently on the market.

Designer Danielle Troffe founded MushLume, a company through which she designs and sells mycelium-based lighting. The Estonian lab, Myceen sells lighting and other MBC products. Other designers and studios including Sebastian Cox, Ninela Ivanova, Olle Sahlqvist, Eric Klarenbeek Studio, Anomalia Studio, AFJD studio, and studio Aléa have made mycelium-based furniture as well.

The aesthetic expression of MBCs in existing work ranges significantly, but many pieces share similar qualities. Significant texture, both visual and physical, exists in almost all MBC work. While many pieces embrace the natural hues of mycelium, very few use color or secondary treatments. Furthermore, as previously discussed, while consumers want the sustainable materiality of MBCs, their typical material expression is off-putting to many. Thus, there is an opportunity to create alternative material expressions for MBCs in efforts to increase consumer desirability. Aesthetics are largely a matter of personal preference; it should be noted that this is not intended to be pejorative of any existing efforts. Rather, this work seeks to propose additional MBC expressions, without implying any are better or worse than others.

Back Stage

"Shroom Packaging" by Mushroom Material

Wine bottle Mushroom Packaging by Ecovative

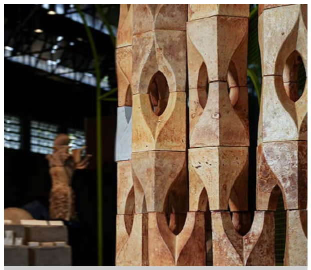
Mycelium drywall insulation, Grown Bio by Ecovative

"Mogu Wave" acoustic tile prototype by Mogu

Fumo Mycelium Wall Panels by MyLab

Front Stage


"Mycelium + Timber" by Sebastian Cox and Ninela Ivanova


MycoMuseum Mycelium Blocks by Anomalia


"SAMOROST" by Buřinka


"The Mycelium Network" by Brain Dead and Space Available


Mycelium Chair by Eric Klarenbeek Studio


"B Wise" mycelium-based pendant lamp by Myceen


Mycelium and wood furniture by Ecovative


"MushLume" lighting by Danielle Troffe


"MyStool" mycelium stool by Olle Sahlqvist


"Zwampen" mycelium lounge chair by Olle Sahlqvist


Mycelium furniture by Phil Ross


Mycelium furniture by Phil Ross


MycoBoard stool by Ecovative


Mushroom furniture by Ecovative and bioMASON


"Back to Dirt" by studio Aléa

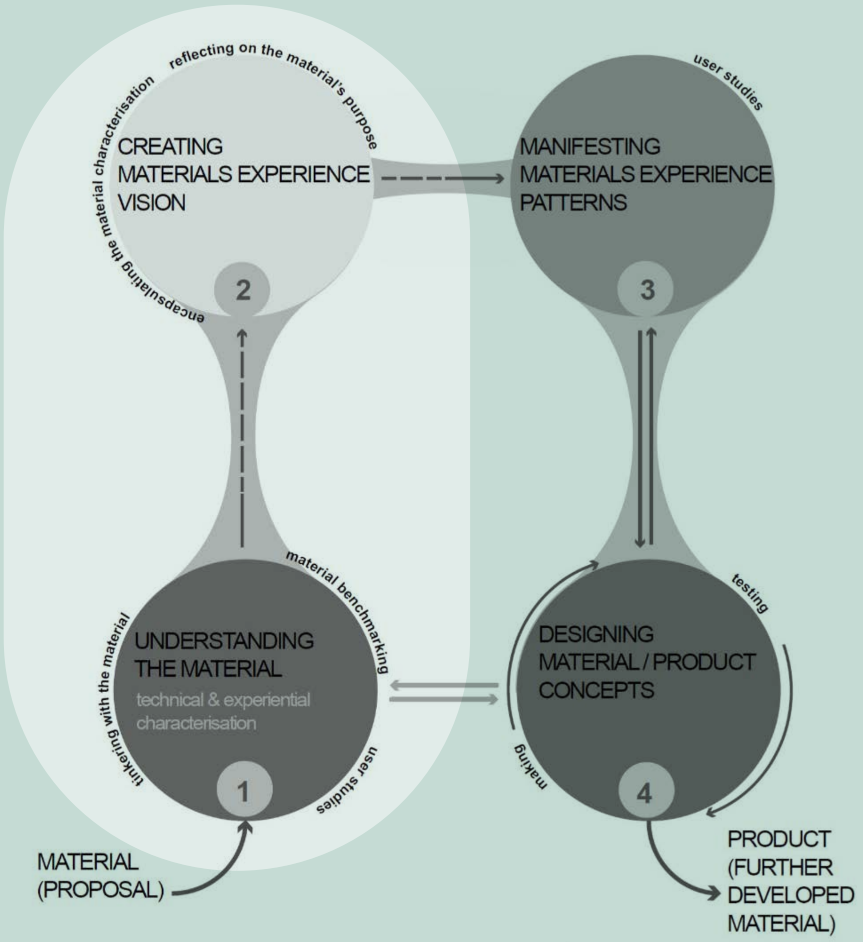

"Foresta System" by Mogu


"BioKnit" by the Hub for Biotechnology in the Built Environment


MushLume "Radiate" Wall Sconce by Danielle Troffe

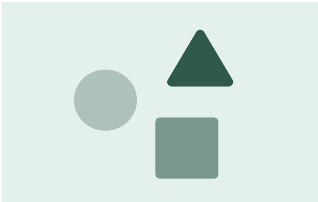

"They Grow Without Us" by AFJD Studio


"Mycelium + Timber" by Sebastian Cox and Ninela Ivanova



This stage of the work falls under phases one and two–understanding the material and creating materials experience vision–of the Material-Driven Design (MDD) process (Karana et al., 2015

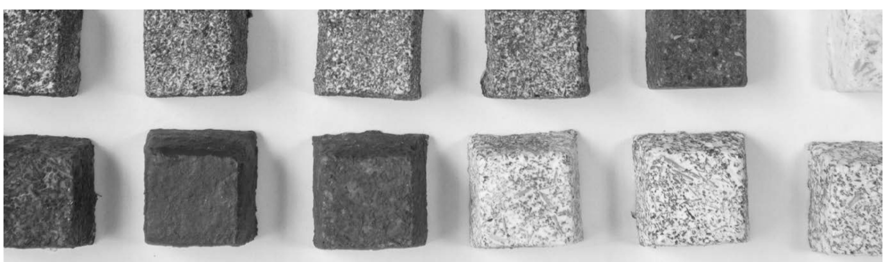
Abstract MBC Investigation



Introduction

Throughout the abstract MBC investigation stage, varied MBC production protocols were investigated. These explored an array of mycelium species, substrate mixtures, processing methods, mold designs, and secondary (post-growth) treatments.

This stage built material understanding and began creating materials experience, phases one and two of the MDD approach. Investigations demonstrated the value of tacit knowledge and ability of MBCs to adopt a vast range of aesthetic and functional expressions, many of which were novel in the greater scope of MBC research.



Coatings, Color, and Consumer Perception

Substrates, Species, Processing, and Texture

Hot Pressing and Reinforcement Fibers

Materials

Ganoderma Lucidum ME-G21 (Reishi mushroom) and Pleurotus Ostreatus ME-P21 (Grey Dove Oyster mushroom) mycelium species were used in this investigation, acquired as liquid cultures from The Mycelium Emporium, located in Enfield, Maine, United States. The liquid cultures were used to create rye grain spawn with rye berries purchased from MushroomMediaOnline.com, which served as the inoculant for the various mycelium spawns that were used and investigated. The substrates explored primarily included combinations of hardwood sawdust, purchased in the form of "Competition Blend" barbeque hardwood pellets made in the United States by Pit Boss Grills, Phoenix, Arizona, United States; ground soybean hulls, purchased as pellets from MushroomMediaOnline.com; and shredded hemp hurd, made by Rural365. The materials used in the coating of MBCs are described in Table 2.

Oyster mushrooms (Pleurotus Ostreatus)

Reishi mushrooms (Ganoderma Lucidum)

Shredded hemp (left), hardwood sawdust (middle), ground soybean hulls (right)

Treatment	Material(s)	Process	Ingredients/Composition
Beeswax Coating	Organic Beeswax Pellets, Yasnay products	Melted beeswax in microwave, applied to swatch with paintbrush when wax temp was ~150°F.	1.5 g beeswax (approximate)
Beeswax Infusion	Organic Beeswax Pellets, Yasnay products	Applied melted beeswax heavily with brush, wrapped swatch in aluminum foil, baked at 190°F in dehydrator until fully absorbed, approximately 1 hour.	4.3 g beeswax (approximate)
Natural Dye (no mordant)	Madder Root Natural Dye, Shepherd Textiles	Dye: extracted at 175-188°F for 4 hours, swatch added and cooked at ~150°F for 3.5 hours. Soaked unheated for 16 hours. Removed.	50% Weight of Fiber (WOF) Madder Root Powder
Natural Dye (with mordant)	Madder Root Natural Dye, Shepherd Textiles; Gallnut Powder, Shree India Trade; Alum Powder (Potassium Aluminum Sulphate), Essencea	Tanin: swatch and gallnut powder added to 180°F water, soaked unheated for 14 hours. Mordant: soda ash and alum added to 180°F water, added swatches (which dropped temp to 140°F), heated for 1 hr until back to 170°F, heat turned off. Soaked unheated for 26 hours. Dye: combined extract/dye at 130-150°F for 9 hours on low heat. Heat off, soaked for 14 hours. Removed swatch.	72% WOF Madder Root Powder 12% WOF Gallnut Powder 2% WOF Soda Ash 20% WOF Alum
Natural Furniture Polish	Daddy Van's All-Natural Beeswax and Lavender with Sweet Orange Oil Furniture Polish	Applied generously to swatch with clean cotton cloth. Buffed excess polish away with fresh cotton cloth after 15 minutes.	Beeswax, Carnauba Wax, Olive Oil, Sweet Orange Oil, Lavender Essential Oil
Oil paint	Refined Walnut Oil, Natural Earth Paint; Mayan Red Earth and Mineral Pigment, Natural Earth Paint	Combined ingredients and mulled on frosted glass slab. Applied 2 coats to swatch with paint brush, 1 day apart.	20:6 Pigment : Walnut Oil
Red Opaque Shellac	Zinsser Bulls Eye Shellac Mayan Red Earth and Mineral Pigment, Natural Earth Paint	Combined the pigment and shellac, applied 2 coats, 1 hour apart.	4:5 Pigment : Shellac
Red Tinted Shellac	Zinsser Bulls Eye Shellac Mayan Red Earth and Mineral Pigment, Natural Earth Paint	Combined the pigment and shellac, applied 1 coat.	2:15 Pigment : Shellac
Refined Linseed Oil	Refined Linseed Oil, Gamblin Artists Colors	Applied to swatch with clean cotton cloth. Excess oil buffed away with fresh cotton cloth after 1 hour.	100% Linseed Oil
Refined Walnut Oil	Refined Walnut Oil, Natural Earth Paint	Applied to swatch with clean cotton cloth. Excess oil buffed away with fresh cotton cloth after 1 hour.	100% Walnut Oil (expeller pressed)
Shellac	Zinsser Bulls Eye Shellac	Applied 2 thin coats with paintbrush, allowing 1 hour in between coats.	Ethanol, Isopropanol, Methyl Isobutyl Ketone, Pure Shellac, Water

Table 2: Description of swatch treatments, their origins, compositions, and application processes.

Coatings, Color, and Consumer Perception

MBC swatches treated with various coatings and dyes.

Coatings and Treatments Study

This experimental-qualitative study investigated the aesthetic and perceptual impacts of coatings and treatments applied to MBCs after their growth and curing, a subject underrepresented in existing research. These novel efforts sought to transform the material semantics and perception of MBCs towards more desirable attributes, informed by the literature review, in ways that are consistent with the CE and appropriate to the material.

Methods

First, small MBC swatches were produced and treated with 12 different dyes, paints, and coatings. The treated swatches were then qualitatively and quantitatively scored on their performance. The criteria for this evaluation were based on a comparative analysis to mature and prolific materials and the literature review of consumer material perception behavior. Initial consumer perceptions were also evaluated with a simple survey. The treatments that performed most desirably as swatches were later applied to a simple luminary prototype and further evaluated with a consumer survey.

Evaluation Methods

Comparable Materials

Mycelium-based composites vary greatly in their material properties depending on the growth and processing procedures used. Some protocols yield lightweight, weak, low-hardness, foam-like materials, while others produce hard, dense, strong, wood-like materials (Sun et al., 2022). Despite this variety, MBCs across the spectrum share a few common features including being opaque and strongest in compression (Vidholdová et al., 2019) and are produced most frequently by molded.

These features are similar to those of ceramic materials like terracotta, stoneware, concrete, and plaster (Thompson & Thompson, 2017, p. 480). Additionally, the use of wood-based aggregates relates to solid wood and wood composites like particleboard in composition and appearance and is visually reminiscent of cork. These materials are also prolific in the design and architectural industries, with precedented applications that demonstrate high aesthetic control and material desirability (Figure #). Consequently, these materials–ceramics, concrete, wood, particleboard, and cork–were chosen as referential/comparative materials to guide the visual direction and evaluation of coatings, represented by the images left.

Comparative material swatches identified based on appearance, composition, use, and material properties.


Ceramic Wall Dish Sconce by Robert Gordon Interiors


Burnt Cork Chair by Noé Duchaufour Lawrance


Eames turned stool by Charles and Ray Eames


Ambiance Sconce by Justice Design Group


Loop Lounge Chair by Willy Guhl for Eternit


Skipper pendant light by Tom Raffield

Selection of consumer products made from identified comparable materials.

Consumer Survey

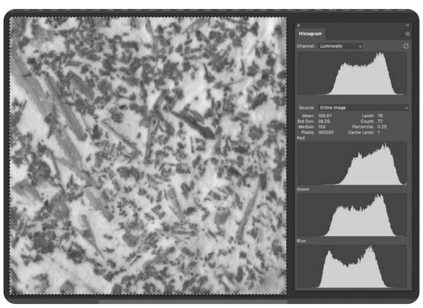
A small group of design students were surveyed to gain preliminary insights into the relationships between swatch treatments and consumer perception. The survey also provided data that helped validate the other evaluations performed.

Questions asked about the swatches:

- Which material sample(s), if any, would you consider using in products?
- In what products or product categories would you use the material?

Evaluation Criteria

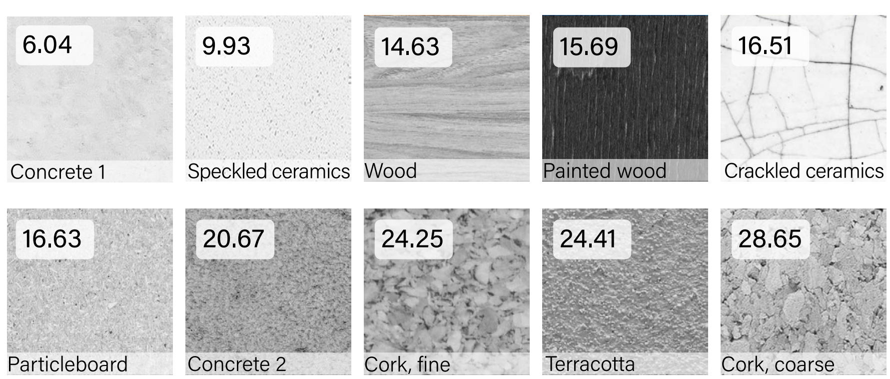
Based on the literature review of design and consumer perception research, the following variables and their methods of assessment have been identified to guide the evaluation of MBC coatings.



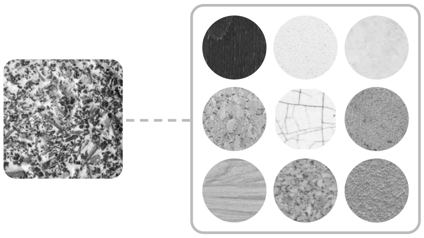
Adobe Photoshop Histogram analysis of swatch scan.

Visual Harmony

The top surfaces of the swatches were scanned in color at 300 dpi on an Epson XP-400 bed scanner. Using Adobe Photoshop, the flat surface (free of contour shadows), sized at 400 x 400 pixels, was isolated at 100% scale. The standard deviations (SDs) of the luminosity of each swatch, obtained through the Photoshop histogram tool, were recorded. These values represent the relative variation in greyscale value amongst pixels in the image, meaning the lower the standard deviation, the greater the visual harmony. While there are limitations to the application of this data, it has demonstrated efficacy in analyzing and grading surfaces (López et al., 2005). The comparison materials were also evaluated in the same way to guide the classification of visual harmony into high, medium, and low levels. The standard deviations for these materials ranged from 6.04 (Concrete 1) to 28.65 (Cork, coarse) with an average of 17.6. Informed by these values, the materials will be sorted into High, Medium, and Low levels of visual harmony, based on SD ranges of <15, 15-29, and >29, respectively



Standard deviation of luminosity for each material comparison, ordered from lowest to highest.

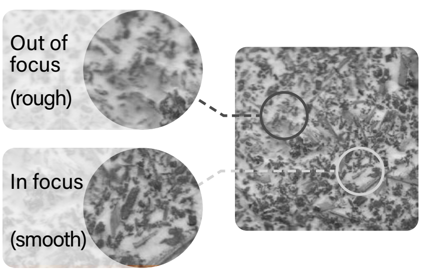


Novelty

The novelty of the swatches is qualitatively assessed based on how similar or dissimilar their appearance is to the comparison material swatches. To simplify this subjective metric, levels are restricted to high, medium, and low.

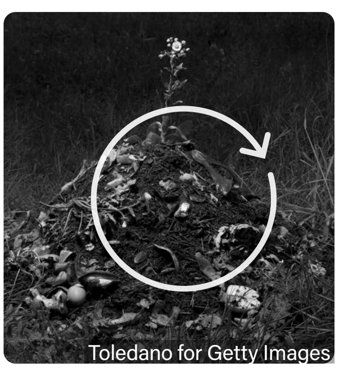
Weight

The weights of the treated swatches are compared to the average weight of the swatches before coatings and treatments were applied, expressed as the percentage of weight difference.



Surface Regularity

The produced swatches will be qualitatively assessed by the author based on tactile surface variability determined through handling the samples, and on visual inspection of the scanned images. Areas of the scanned swatch images that are out of focus indicate that they are recessed in the swatch, thus the more in focus a swatch scan is, the more regular its surface.


Toledano for Getty Images

Conceptual Consistency

The conceptual consistency is considered in respect to the material's appearance, physical composition, and contextual background cohesiveness. The physical composition and contextual background refer primarily to the high sustainability and circularity potential of MBCs, especially since the swatches do not have product application context. Thus, put simply, this variable asks to what degree the material looks natural and environmentally sustainable, particularly in comparison to the uncoated control swatch.

Coating and Treatment Selection Criteria

Common woodworking and other surface treatment coatings were considered for use in this research. 12 coatings and treatment methods were selected based on the following criteria, also informed by the literature review:

- Biodegradability – the coating material must be readily biodegradable.
- Inferred potential – the coating material should have precedented efficacy or demonstrated potential in relatable applications (like woodworking and bioplastics fields)
- Accessibility – the coating material should be readily available in local, national, and global contexts.
- Breadth – coating materials with very similar properties will not be compared to maximize breadth of exploration. For example, only two drying oils (walnut oil and linseed oil) were chosen as there is existing documentation that compares drying oils to one another.

Coating and Treatment Selections

Beeswax

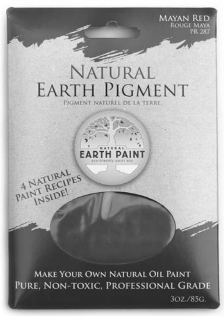
Beeswax is a natural, animal-derived wax made by honeybees, and harvested as a by-product of the honey production process. It is water resistant, naturally white in color, non-toxic, and biodegradable (Tinto et al., 2017). It also has precedented success with waterproofing other biodegradable polymers, making it an enticing choice for this research (Hendrawati et al., 2021).

Shellac

Shellac is a natural, biodegradable protective coating and adhesive material with a strong cultural and historical background, dating as far back as the 12th century, especially in Asia where it originated. Secretions made by lac insects which live on various woody plants are processed using one of many possible methods into coating materials for use in carpentry, cosmetic, food, construction, and other applications (Thombare et al., 2022). It was chosen due to its unique combination of water resistive, protective, non-toxic, and biodegradable properties.

Refined Walnut and Linseed Oils

Refined walnut oil and refined linseed oil are widely available drying oils that are used frequently by woodworkers and artists as a finishing oil and paint medium. A drying oil is an oil that dries and hardens into a protective finish through polymerization. These oils are biodegradable, safe, and natural, and chosen because of their precedence in carpentry and fine arts applications (Segura, 2021).



Natural Earth Pigment

Color plays a significant role in aesthetic expression, es established in the literature review, but most coating materials, including those chosen for this research, are relatively colorless. Thus, a natural earth pigment was chosen to colorize shellac in two varying opacities and walnut oil, as one method to explore color integration in MBCs. Mayan Red pigment from Natural Earth Paint, was chosen as it provides high variation to the common natural tones innate to MBCs. It is also non-toxic, archival, and biodegradable (All About Pigments, n.d.).

Hybrid Materials

Hybrid combinations of the above materials were also selected for this research. These include a commercial All-Natural Furniture Polish, homemade oil paint, opaque tinted shellac (referred to as “shellac paint”), and translucent tinted shellac (referred to as “shellac tint”). The furniture polish was chosen because it combines desirable properties of its ingredients (which are outlined in Table 1) and is commonly used by consumers and woodworkers for wood-based materials (Segura, 2021).

Natural Dye - Madder Root

Madder, or Rubia tinctorum, is a flowering plant that, when mature, produces a vibrant, lightfast red dye. Originating in West Asia, it possesses a strong cultural background and has been used for centuries to dye textiles. It was chosen for this research because dye methods are thoroughly documented, and the red hue mirrors the red pigment used. (Dyeing With Madder Root (Rubia Tinctorum), n.d.). When dyeing textiles with natural materials, must first be treated pretreated with certain materials (tannins, mordants, chalks) so the dye fixes to the fiber. There are no documented methods of dyeing MBCs with natural sources, so one sample was dyed with no pre-treatment, and one was treated with the same tannin and mordant process used when dyeing cellulose fibers.

Sample Preparation

Spawn Production

The mycelium spawn used in the swatches and luminary prototypes was prepared using standard mycelium production techniques. First, substrate was prepared by combining 400g hardwood sawdust, 400g soybean hulls, 200g shredded hemp, and 1666g water each into two filtered polypropylene autoclavable mushroom grow bags. This mixture was then pressure sterilized at 121°C and 15 PSI for 60 minutes. Once cooled to room temperature, the sterilized substrate was inoculated in sterile conditions under a laminar flow hood with 75g of Ganoderma Lucidum grain spawn in each bag. The bags were sealed and the inoculant thoroughly distributed into the substrate by shaking. The bags were then incubated for 11 days in a slightly warm and humid environment. Due to resource limitations, it was not possible to precisely control the environmental conditions, namely temperature, humidity, and carbon dioxide levels, all of which impact mycelial growth. Despite this, occasional monitoring of the temperature and humidity levels in the incubation environment indicated that conditions remained semi-consistent between 70-75°F (21-24°C) and 50-85% relative humidity. After this period, visual assessment confirmed complete colonization, and the bag was transferred to a refrigerator and stored at 40°F (4.4°C) until molding.

Sterilized grow bags ready for inoculation.

Swatches at key stages of growth.

Swatches

Simple tapered cubes were modeled in Solidworks and 3D printed in PLA+ filament (Elegoo brand). The cubes featured a 4x4 cm top face, 4 cm height, 10° draft angle, 3mm radius on internal corners, and a thin grove placed at 3 cm to mark the molding height. To fabricate the swatches, using sanitized instruments in front of a laminar flow hood, a portion of the prepared spawn was removed from the bag, placed in a large plastic container, and broken up by hand. Next, the spawn was blended in a food processor for 30 seconds, approximately 100 g at a time. This process, while an effective way to thoroughly break apart the spawn, proved to be prohibitively time consuming, so this step was omitted from the prototype fabrication. This was due to the friction during blending, which quickly heated the spawn before the full 30 seconds. Each time the temperature, monitored with an infrared thermometer, reached 85°F (29.4°C), blending was stopped until the temperature decreased to mitigate damage to the mycelium. 40.4 g +/- 0.5 g of blended spawn was added to each swatch mold. The filled mold was tapped on the table surface 20 times, then the spawn was compressed by hand down to the 3 cm height mark. The samples were placed in a plastic container, modified with filter patches to promote gas exchange, and incubated for 7 days in the same conditions as the spawn. Next, the samples were demolded and returned to the container for 4 additional days of incubation. This secondary growth period promotes increased mycelial density, especially on the object surface, forming a fungal skin. Finally, the samples were removed from the container and dried at 150°F (65.6°C) for 24 hours in a consumer food dehydrator, using weight monitoring to ensure complete dehydration. A total of 15 swatches were produced.

Swatch Treatments

The coating and treatment procedures applied to the swatches are described in Table 3 below. Each treatment was applied to one swatch.

Table 3: Materials and processes of the applied swatch treatments.

Treatment	Material(s)	Process	Ingredients/Composition
Beeswax Coating	Organic Beeswax Pellets, Yasnay products	Melted beeswax in microwave, applied to swatch with paintbrush when wax temp was ~150°F.	1.5 g beeswax (approximate)
Beeswax Infusion	Organic Beeswax Pellets, Yasnay products	Applied melted beeswax heavily with brush, wrapped swatch in aluminum foil, baked at 190°F in dehydrator until fully absorbed, approximately 1 hour.	4.3 g beeswax (approximate)
Natural Dye (no mordant)	Madder Root Natural Dye, Shepherd Textiles	Dye: extracted at 175-188°F for 4 hours, swatch added and cooked at ~150°F for 3.5 hours. Soaked unheated for 16 hours. Removed.	50% Weight of Fiber (WOF) Madder Root Powder
Natural Dye (with mordant)	Madder Root Natural Dye, Shepherd Textiles; Gallnut Powder, Shree India Trade; Alum Powder (Potassium Aluminum Sulphate), Essencea	Tanin: swatch and gallnut powder added to 180°F water, soaked unheated for 14 hours. Mordant: soda ash and alum added to 180°F water, added swatches (which dropped temp to 140°F), heated for 1 hr until back to 170°F, heat turned off. Soaked unheated for 26 hours. Dye: combined extract/dye at 130-150°F for 9 hours on low heat. Heat off, soaked for 14 hours. Removed swatch.	72% WOF Madder Root Powder 12% WOF Gallnut Powder 2% WOF Soda Ash 20% WOF Alum
Natural Furniture Polish	Daddy Van's All-Natural Beeswax and Lavender with Sweet Orange Oil Furniture Polish	Applied generously to swatch with clean cotton cloth. Buffed excess polish away with fresh cotton cloth after 15 minutes.	Beeswax, Carnauba Wax, Olive Oil, Sweet Orange Oil, Lavender Essential Oil
Oil paint	Refined Walnut Oil, Natural Earth Paint; Mayan Red Earth and Mineral Pigment, Natural Earth Paint	Combined ingredients and mulled on frosted glass slab. Applied 2 coats to swatch with paint brush, 1 day apart.	20:6 Pigment : Walnut Oil
Red Opaque Shellac	Zinsser Bulls Eye Shellac Mayan Red Earth and Mineral Pigment, Natural Earth Paint	Combined the pigment and shellac, applied 2 coats, 1 hour apart.	4:5 Pigment : Shellac
Red Tinted Shellac	Zinsser Bulls Eye Shellac Mayan Red Earth and Mineral Pigment, Natural Earth Paint	Combined the pigment and shellac, applied 1 coat.	2:15 Pigment : Shellac
Refined Linseed Oil	Refined Linseed Oil, Gamblin Artists Colors	Applied to swatch with clean cotton cloth. Excess oil buffed away with fresh cotton cloth after 1 hour.	100% Linseed Oil
Refined Walnut Oil	Refined Walnut Oil, Natural Earth Paint	Applied to swatch with clean cotton cloth. Excess oil buffed away with fresh cotton cloth after 1 hour.	100% Walnut Oil (expeller pressed)
Shellac	Zinsser Bulls Eye Shellac	Applied 2 thin coats with paintbrush, allowing 1 hour in between coats.	Ethanol, Isopropanol, Methyl Isobutyl Ketone, Pure Shellac, Water


BEESWAX COATING
REFINED LINSEED OIL
BEESWAX INFUSION
REFINED WALLNUT OIL
MADDER ROOT DYE (DYE ONLY)
SHELLAC
MADDER ROOT DYE (MORDANTED)
SHELLAC + PIGMENT (PAINT)
ALL NATURAL FURNITURE POLISH
SHELLAC + PIGMENT (TINT)
HOMEMADE OIL PAINT
NO COATING

Results

Swatch Evaluation

Using the established metrics of evaluation, the produced swatches were rated on their performance in each category in Table 4. In addition to the perceptual metrics–visual harmony, novelty, weight, surface regularity, and conceptual consistency–coating transfer was added as a performance metric. This was added after some coatings were observed staining surfaces or other material swatches. Treatments that had no transfer were ranked most favorably.

The highest and lowest performances within each metric were highlighted green and orange, respectively, to help visualize the overall performance of each swatch. Two swatches, shellac and shellac paint, performed favorably in 4 categories, establishing them as the two most promising treatments. Beeswax infusion, natural polish, and shellac tint performed well in three categories, but the shellac tint performed unfavorably in two, whereas beeswax infusion and natural polish only performed unfavorably in one. Thus, they were identified as the two next most promising treatments.

Photo	Treatment	Weight (% heavier)	Luminosity Standard Deviation	Visual Harmony	Novelty	Surface Regularity	Conceptual consistency	Coating Transfer
	Beeswax Coating	+14	23.32	Med	High	High	High	No
	Beeswax Infusion	+35	28.77	Low	Med	Med	High	No
	Natural Dye (no mordant)	-3	14.32	High	Med	Low	Med	Med
	Natural Dye (with mordant)	-3	11.65	High	Med	Med	Med	Low
	Natural Furniture Polish	+3	33.75	Low	Med	High	High	Low
	Oil paint	+26	5.65	High	Low	High	Low	High
	Refined Linseed Oil	+4	38.25	Low	High	Low	High	Med
	Refined Walnut Oil	+20	36.18	Low	High	Low	High	Med
	Shellac	+5	33.58	Low	Med	High	High	No
	Shellac Paint	+20	10.34	High	Med	High	Low	No
	Shellac Tint	+10	11.52	High	Med	Low	Low	No
	Uncoated(control)	0	15.74	Med	High	Low	High	N/A

Table 4: Evaluation of treated swatches

Additional Efforts with Coatings and Treatments

MBC swatches treated with various dyes and coatings.

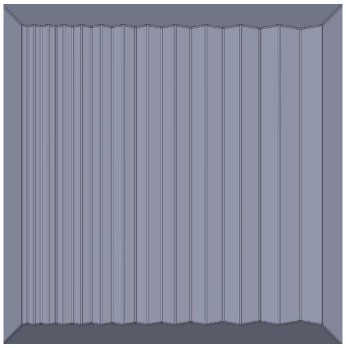
Following the formal study, additional swatches were treated with an additional series of dyes, infusions, and coatings. A set of swatches were infused with shellac mixtures of various solvent ratios to investigate the impacts on shellac penetration. Additional methods of dye application were also explored, including the use of alcohol-based solvents (denatured alcohol, 99% isopropyl alcohol, 70% isopropyl alcohol). As described in the literature, mycelium itself is hydrophobic, while the substrates on which it grows tend to be hydrophilic. Due to its hydrophobicity, previous efforts to dye mycelium were very time intensive. Alcohol, however, is readily absorbed by the mycelium, and the explorations demonstrated that both alcohol-based dyes and pre-dye alcohol surface treatments offer effective methods to deposit dyes on MBCs. The light- and colorfastness of these dyes, however, are yet to be explored and should be investigated further. The use or omission of mordants should also be explored in further detail, alongside the effects of additional surface coatings like shellac on dye longevity.

Substrates, Species, Processing, and Texture

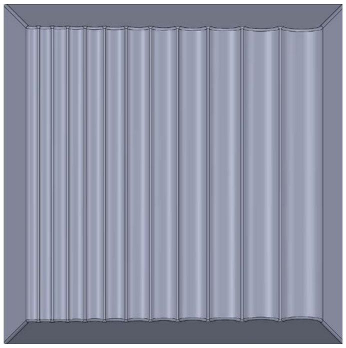
Overview

This exercise explored relationships between mycelium species, substrate composition, substrate processing method, and final composite texture. Both reishi and oyster mushroom mycelium was grown on substrates comprised of hardwood sawdust, soybean hulls, and hemp hurd in varying ratios. These blends were processed by hand and with a food processor for different durations before being molded into two forms, one with sharp pleats, one with rounded scallops.

Pleats (form 1)



Scallops (form 2)



Methods

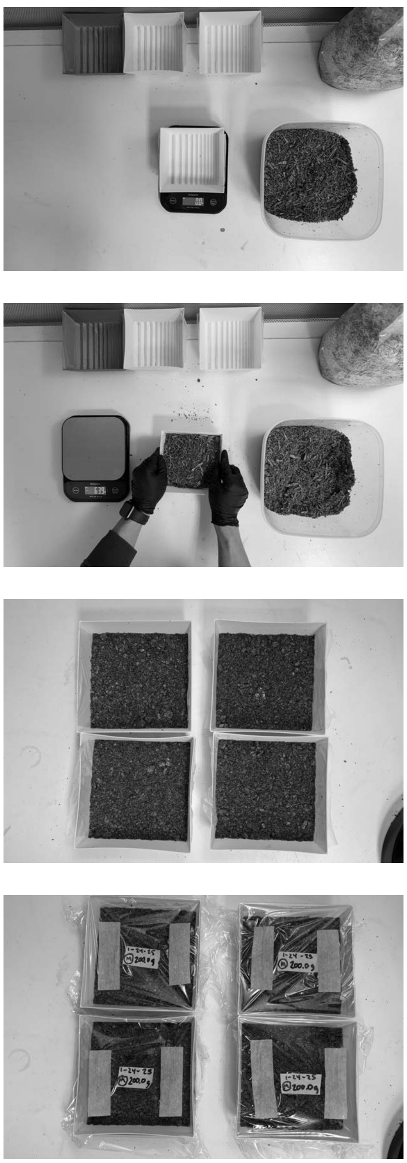
Mold Design

The two forms used in this study were designed to showcase the texture scale and fidelity each of the varied protocols produced. Each feature a top surface textured with 12 sections that increase regularly in width. Form 1 features sharp peaks or pleats, while form 2 features rounded bumps, or scallops. Eight molds of each design were 3D printed with PLA filament.

Spawn fragmentation in food processor.

Varied Procedures

Samples and sample sets with varied production protocols were produced to gain insight on the they affect the aesthetic (specifically textural) presentation of the finished composites. All substrates contained a "Master's Mix" base, comprised of 50% hardwood sawdust, 50% ground soybean hulls. Varied substrates with different amounts of added shredded hemp were prepared for each mushroom species. The method fragmentation, or breaking up, of the colonized mycelium spawn was also varied. For some samples, the spawn was broken up by hand until visually uniform, for others, it was blended in a food processor for a set duration.


Mold packing process.

Constants

The molds, growing conditions, and molding, and demolding procedures remained constant across all samples. Each mold was first lined with grippy cling wrap pressed tightly to the interior mold surface. Next they were packed with 200.0 g of fragmented spawn and tapped on the bench-top 80 times to help evenly disperse and settle the spawn which was then hand-compacted until firm. The packed molds were then covered in plastic wrap with added slits and filter tape to promote airflow and prevent contamination. After 1 week of growth, the samples were demolded and transferred to a closed container for the second stage of growth.


Molding setup.

Results

Substrate

Substrate composition had a demonstrable effect on the texture of the produced composites. Substrates with no hemp produced the most precise and consistent textures, both within the material and adherence to the mold texture. Mixtures with hemp still conformed to the mold texture, but to a lesser degree and with significantly more surface irregularities. The hemp-inclusive samples, however, shrank and warped less upon drying.

Oyster mycelium samples containing 30% (left) and 20% (right) hemp.

Species

The mycelium species also had a profound effect on the final composites. The oyster mycelium produced a fluffy, cloud-like thick fungal skin layer that is soft to the touch. The reishi mycelium produced a fungal skin that hugged the surface of the molded substrate more closely, and was less smooth and soft to the touch. Both species exhibited some variation in color between and within samples, likely due to the maturity of the mycelium or external contaminants. Reishi samples were brighter white, while oyster samples adopted a warm yellow tint.

Reishi (left) and oyster (right) samples.

Processing

Fragmentation methods also affected the final samples. Samples whose spawn was broken apart using the food processor resulted in more visually prolific growth and better texture homogeneity than those that used manual fragmentation. The use of a food processor posed issues with contamination and damage to the spawn, however. The friction created during blending could rapidly increase the temperature of the spawn. In a few cases, this weakened the spawn, leaving it susceptible to mold contamination, ultimately resulting in failed samples. Despite these challenges, with a more robust or customized blending process, the use of automated and high-speed fragmentation could be highly fruitful.

Samples that experienced contamination during growth.

* Indicates contamination during growth

Key Findings

- Reishi mycelium grows a more defined surface skin while Oyster mycelium grows a fluffy, cloud-like skin.
- Smaller substrates result in finer, more regular textures.
- Breaking up the spawn more results in more prolific growth and more regular textures.

Other Observations

- PLA molds warp and get bound to the MBC at humidities above ~85%.
- Oyster composites shrink less.
- Larger substrates warp and shrink less upon drying.

Hot Pressing and Reinforcement Fibers

Overview

This investigation sought to explore relationships between added longitudinal fibers and composite strength in hot pressed panels. Three varied fibers–coconut coir, soybean roving, and fine bamboo flakes–were chosen as the added fibers for the composites based on observations from previous work and literature reviews.

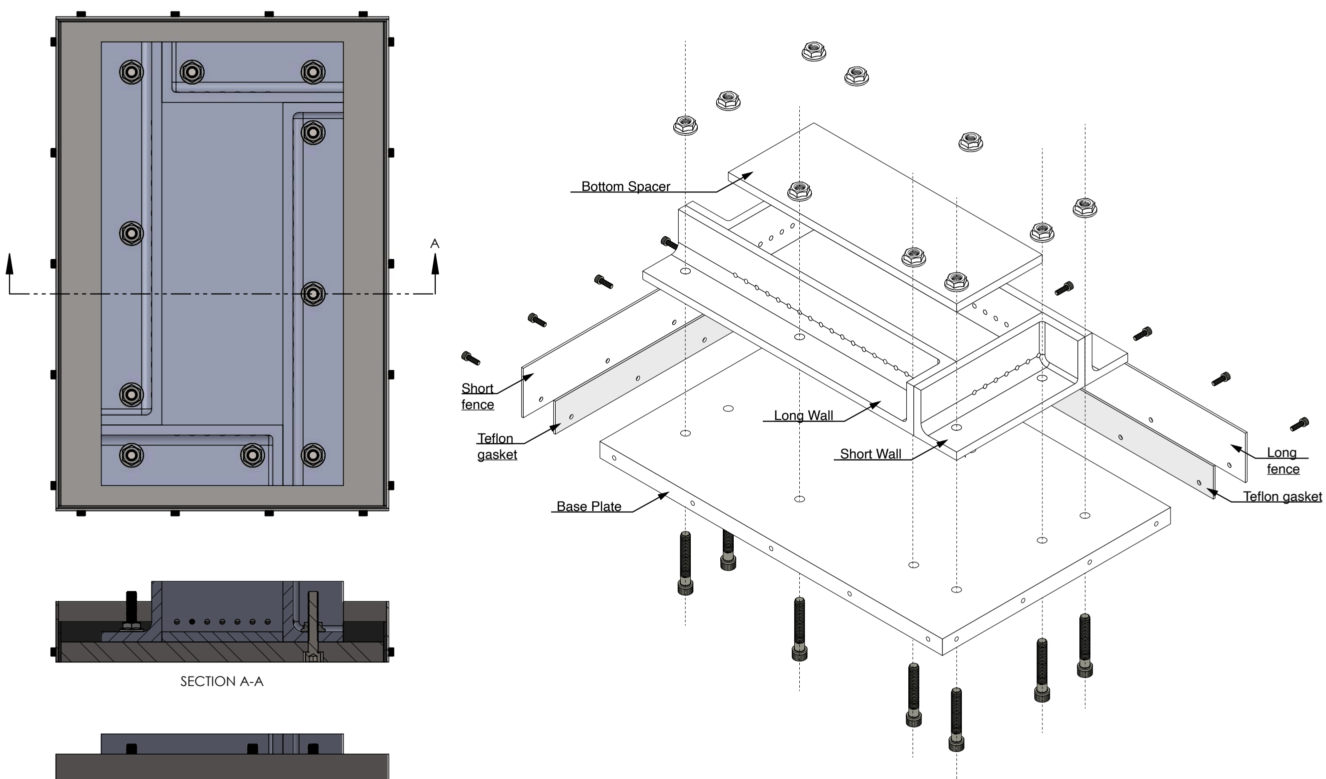
Methods

Mold Fabrication

8 plastic-lined plywood molds (8×3×3″ interior) were built to mold the initial composites. Using pocket holes and modular assembly, the molds are durable and reusable.

The compression form (8×3×1.5″ interior) was machined from A36 steel. The base is 1/2″ steel with 1/4″ counter-bored through holes to secure the form walls. The form walls are made from 9.5″ and 4.5″ sections of 1 1/2″ x 1/4″ angle steel. The walls have through holes that align with the base and ventilation holes to permit moisture to escape during pressing. A 1/4″ spacer and 1″ plunger were used to compress the panel to its final height.

Machining of a form wall.



CAD Drawings of the compression form.

Mycelium Spawn and Fiber Preparation

First, spawn was prepared by combining 500g soybean hulls, 500g hardwood sawdust, and 1.67L water in grow bags. The bags were sterilized in an autoclave at 121°C (15psi) for 60 minutes, cooled to room temperature, and inoculated with 300g Reishi spawn. Next, the bags were Incubated at 21–24°C and 50–80% humidity for 1 week until fully colonized.

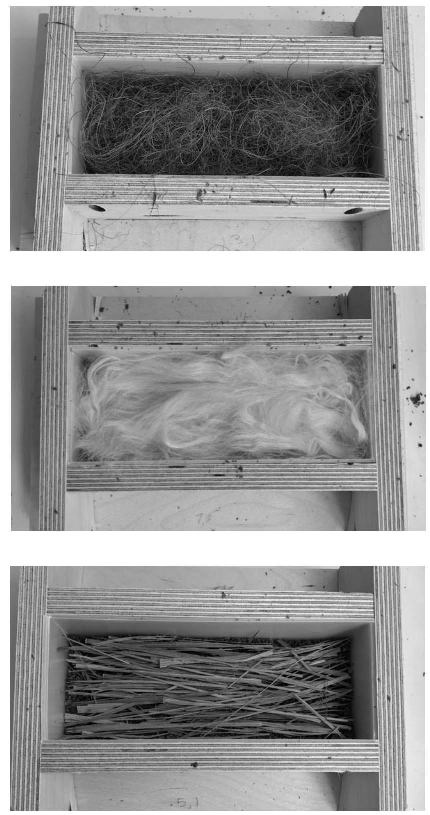
Prior to molding, the test fibers (bamboo flakes, coco coir, soybean roving) were sterilized using the same process.

Fibers in jars prepared for sterilization

Molding Samples

Two samples of each fiber type and two control samples with no added fiber were molded. First, the prepared mycelium spawn was broken apart using a food processor with a dough blade. The samples were then molded with the following procedures and covered in plastic wrap to prevent contamination.

Plywood molds and mycelium spawn on laminar flow hood bench.



Coconut coir, soybean roving, and bamboo fiber layers during molding.

Control samples:

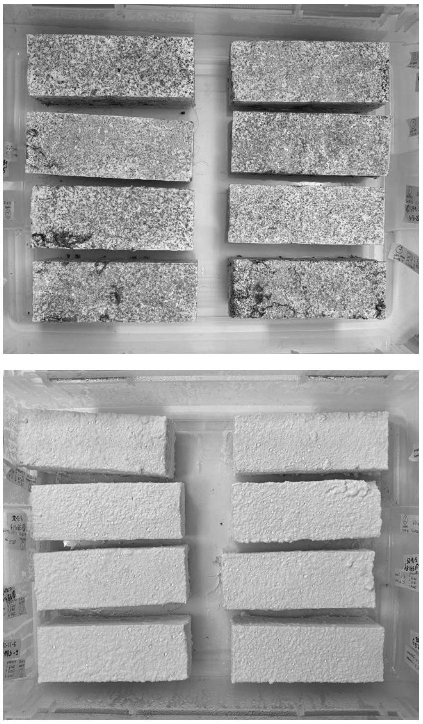
610g of blended mycelium spawn was added to each mold and compacted by hand to top of the mold.

Fiber samples:

The fiber samples were molded by layering mycelium spawn and the added fiber. The layers consisted of 200g spawn, 5g fibers (oriented lengthwise along the sample), 200g spawn, 5g fibers (same orientation), and 200g spawn. The samples were compacted by hand to the top of the mold.

#	Fiber	Spawn weight (g)	Fiber weight (g)	Spawn weight (g)	Fiber weight (g)	Spawn weight (g)	Total molded weight (g)
1	n/a	610.5	--	--	--	--	610.5
2	n/a	610.6	--	--	--	--	610.6
3	Coco coir	200.4	5.1	200.8	4.9	199.5	610.7
4	Coco coir	200.6	5.0	200.0	5.1	200.9	611.6
5	Bamboo flakes	200.0	4.9	200.4	5.0	200.8	611.1
6	Bamboo flakes	200.0	5.1	200.3	5.0	200.8	611.2
7	Soy roving	200.0	5.0	200.3	5.0	200.1	610.4
8	Soy roving	200.6	5.1	200.1	5.0	200.4	611.2

Table 5: Weights of molded spawn and fiber.



Samples before (left) and after (right) the second stage of growth.

Samples Growing

After 6 days of growth, the samples were removed from their molds and transferred to a container for a second stage of growth. The second stage of growth encourages a dense mycelium skin (aka fungal skin) to form on the exterior of the samples. This stage was 15 days.

Samples drying in dehydrator (top) and sample rehydrating with controlled moisture content (bottom)

Conditioning Samples

The samples were dehydrated until fully dry using a food dehydrator. Weight measurements were taken incrementally to track change in weight (changes in moisture level). Once fully dry, the samples were rehydrated to approximately 15% moisture content. This conditioning stage was completed because before dehydration, the samples contain roughly 70% moisture content, which is far too high for heated pressing as it would create dangerous levels of steam and expelled moisture.

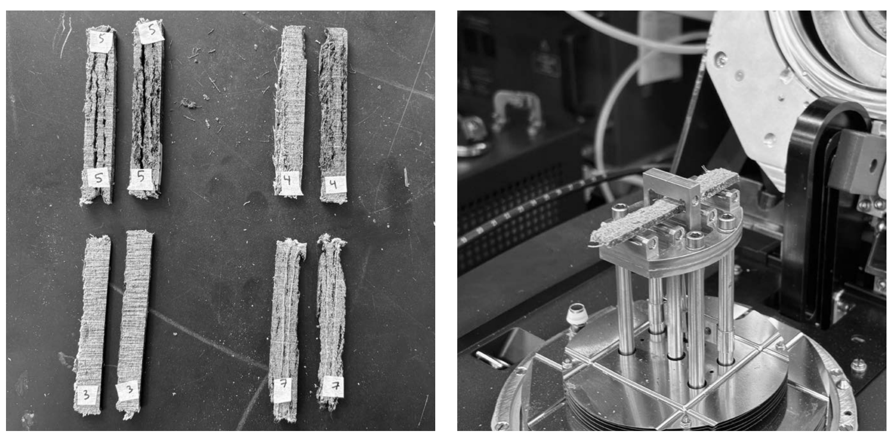
Pressing Samples

The samples underwent hot-pressing in a Teflon-lined steel form, beginning with cold pre-compression to seat the plunger. Each sample was then pressed at 200°C under 10 tons of pressure while monitoring internal temperature. Due to lack of procedural consistency and documentation in existing literature, the appropriate press duration was unknown, so compression timing varied between samples in pursuit of optimal conditions. Variable press times revealed critical findings and emphasized the need for process refinement. More samples should have been prepared and pressed during a discovery or calibration phase that determined the necessary timings. Sample 1 showed lower density due to press height error, and all samples experienced steam blowout causing delamination upon pressure release. Longer press durations reduced blowout severity, highlighting the need for standardized press conditions and improved moisture control in future trials. The Teflon lining proved effective for demolding despite these challenges.

#	Fiber	Weight before press (g)	Moisture content	Press temp (°F)	Press pressure (tons)	Press duration (minutes)	Weight post press
1	n/a	206.1	3%	390	10	10	200.2
2	n/a	--	--	--	--	--	--
3	Coco coir	215.6	12.5%	390	10	15	188.6
4	Coco coir	216.7	16.9%	390	10	20	180.0
5	Bamboo flakes	217.4	15.8%	390	10	18	183.1
6	Bamboo flakes	--	--	--	--	--	--
7	Soy roving	216.1	14.7%	390	10	12	184.3
8	Soy roving	--	--	--	--	--	--

Table 6: Cut panel sections labeled and prepared for testing (left), section from panel 3 in the testing configuration before testing (right)

Sample during pressing, from left to right: uncompressed, post cold pressing, post hot pressing.



Cut panel sections labeled and prepared for testing (left), section from panel 3 in the testing configuration before testing (right)

Testing Samples

Sections of the samples were cut out using a band saw for material testing. Unfortunately, the internal blowout issues encountered during pressing made most samples fall apart during cutting, meaning they couldn't be tested. Sample 3 stayed together the best and afforded testing. One section of sample 3 was tested in 3 point bending, yielding maximum stress of approximately 0.175 MPa (Figure 1). This may indicate that coco coir is the more effective fiber, or that the press timing of this sample was most optimal, but additional work is needed to investigate.

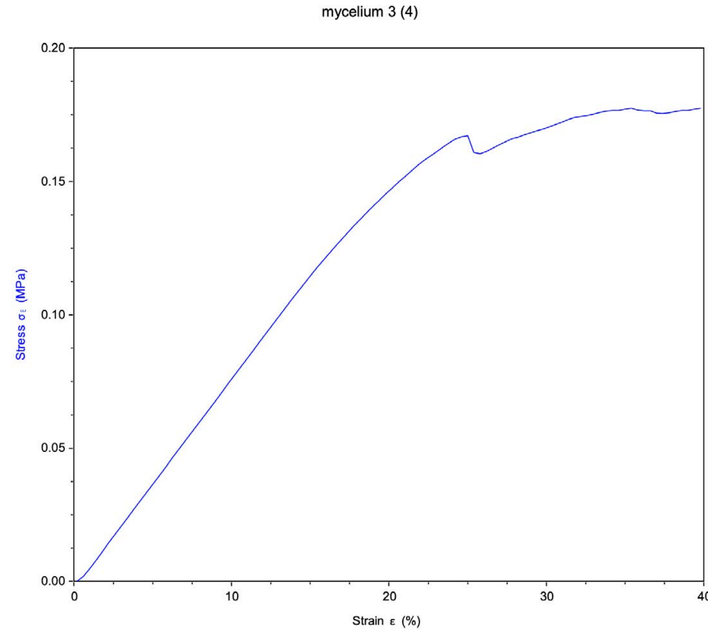


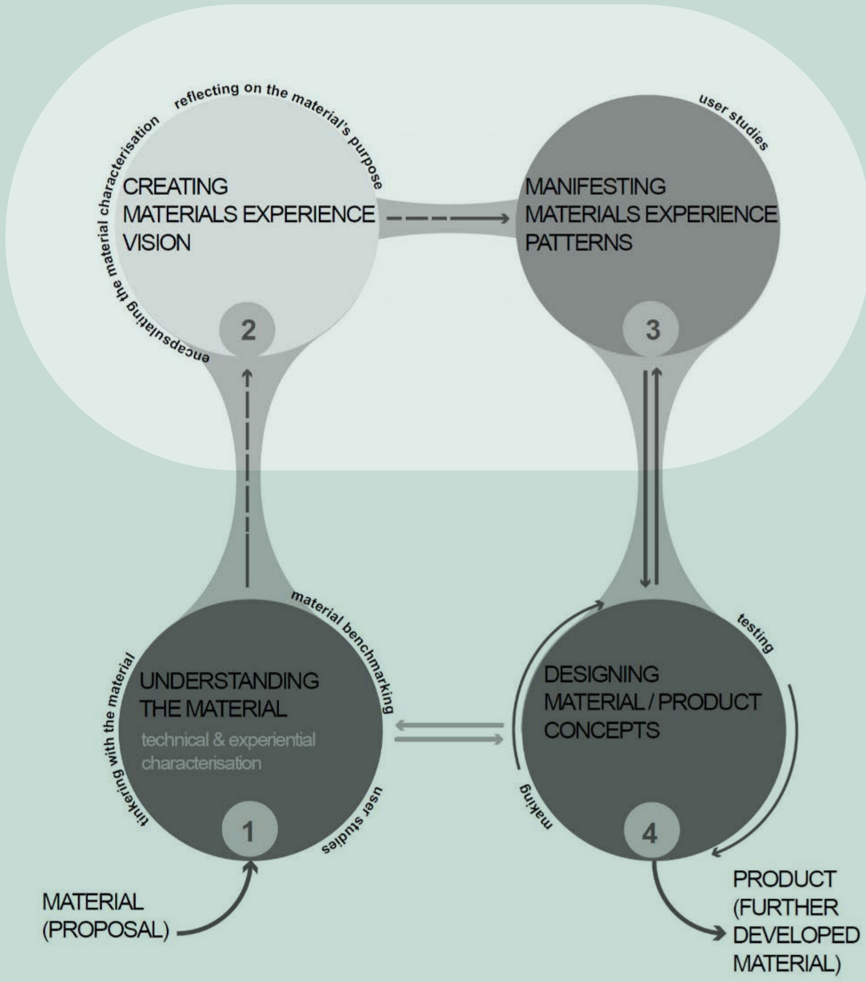
Figure 1: Stress-strain curve results of testing one cut section from sample panel under 3-point bending

Results

While procedural errors the quantitative data produced by this study, additional tacit knowledge on MBC material behaviors was gained. The strength and hardness of the composites increased significantly with hot-pressing. The use hot-pressing restricts shrinking to the desired dimension, while the use of longitudinal fibers reduced shrinking in uncompressed panels. The dehydration protocol was effective, but steam blowout still occurred and press conditions need further refinement. Finally, significant internal delamination occurred in the samples at the longitudinal fibers layers. This suggests that the added substrates may not be readily digestible by the mycelium, or that procedural changes are needed to optimize internal cohesion.

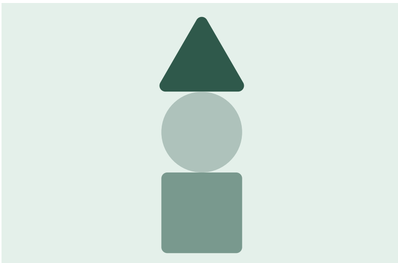
Hot pressed samples 1, 3, 5, and 7.

Sample 5 before (left) and after (right) hot pressing.



This stage of the work falls under phases two and three of the Material-Driven Design (MDD) process; creating materials experience vision, and manifesting materials experience patterns (Karana et al., 2015).

Semi-Applied MBC Investigation



Introduction

The semi-applied MBC investigation stage built on findings from the abstract investigations to begin bridging abstract and practical material and product demands. Focused on expanding materials experience vision and manifesting materials experience patterns, ideation and rapid prototyping were utilized in pursuit of a mature, material-driven design.

Luminary

Stool

Mood Board

A series of works were selected to guide the design process. Formal, aesthetic, and functional inspiration were taken from the precedents shown in pursuit of a desirable and mature front-stage mycelium-based luminary and stool.


Cylinder Ribbon Wall Sconce
by Hooks and Lattice


Santa Inez Sconce
by A19


MushLume "Radiate" Wall Sconce
by Danielle Troffe


Ceramic Wall Dish Sconce
by Robert Gordon Interiors


Burnt Cork Chair by
Noé Duchaufour Lawrance


Eames turned stool
by Charles and Ray Eames


Ambiance Sconce
by Justice Design Group


Loop Lounge Chair
by Willy Guhl for Eternit


Skipper pendant light
by Tom Raffield


Corks
by Jasper Morrison


Nontalo stool
by Eneris Collective and NaifactoryLAB


Eames turned stool
by Charles and Ray Eames


Wiid Stacked African Cork Stool
by Laurie Wiid van Heerden


Refoam furniture
by We+


Bit Stool
by Normann Copenhagen


Wiid Stacked African Cork Stool
by Laurie Wiid van Heerden

Luminary

V1

Render of luminary design V1

Design

Inspired by mid-century and postmodern forms, and in pursuit of radical new MBC semantic presentations, the luminary V1 design featured a traditional table lamp posture with crisp radial pleats and precise geometric conditions. Such geometries proved challenging to mold in MBCs. A series of prototypes with altered scales, mycelium species (*Pleurotus Ostreatus* and *Ganoderma Lucidum*), substrate combinations, mold designs, and mold materiality were produced.

Rapid prototyping of luminary design V1 revealed many conflicting features of the design and material.

Results

Prototype results varied slightly between iterations, but all revealed incompatibilities between the design and material application. None of the iterations produced the precision of pleats desired, and the texture of the material competed with the texture of the form.

Additionally, the joint between the head and body of the form was weak across most versions, and demolding issues occurred frequently. Using a 6-part TPU (thermoplastic polyurethane) mold that separated the head and body yielded improved results over a 4-part PLA mold, but demolding was inconsistent and in most cases, some spawn stuck to the mold, creating voids or cracks in the final form. Drying the samples increased the intensity of the material texture and further obfuscated the formal texture. Efforts to hollow out the form so lighting wiring could be passed through led to thin walls and mold complications.

In all, rapid prototyping revealed that this design is not readily compatible with mycelium-based materiality.

V2

Redesign

After numerous obstacles to molding V1, the luminary was radically redesigned, guided by the following considerations:

Moldability

The design must readily afford being molded out of MBCs.

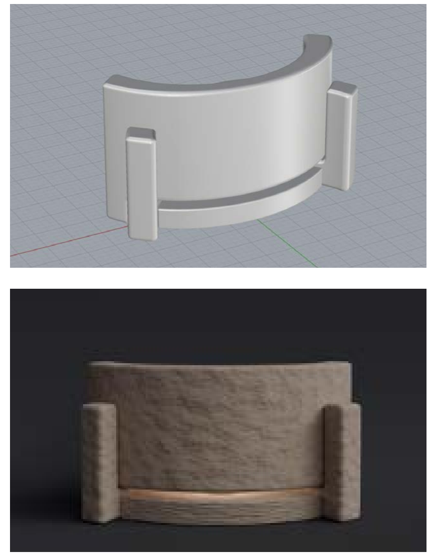
Material Limitations

MBCs are strongest in compression and due to relatively low tensile strength, require an amount of uniform thickness to avoid points of failure (i.e., thin, delicate, fin-like features do not lend themselves to be made from non-densified MBCs).

Material Expectations

MBCs are opaque materials and should be treated as such, especially regarding the diffusion of lighting.

During the design process, CAD and rendering software was used to assess conformity to the established considerations. 3D models, made in Rhino 8 were rendered with custom mycelium textures and lighting components to assess the diffusion of lighting, and geometry evaluation tools were used to assess moldability and guide the final mold design.



`CAD-assisted evaluation of the luminary V2 design, assessing moldability and textural presentation.

Prototype Fabrication

A series of V2 prototypes were produced, some with minor variations in substrate composition, informed by previous abstract investigations. To create the models, molds were 3D printed, assembled, and sanitized with 70% isopropyl alcohol. In front of a laminar flow hood, the prepared spawn was broken apart by hand until all clumps were homogeneously separated. This spawn was then packed into molds and compressed firmly by hand. After growing for one week, the model parts were then demolded, assembled, and incubated for an additional 4-7 days until visual inspection revealed a consistent fungal skin layer. The parts for one luminary were kept separate during the secondary growth stage and assembled after curing. The models were then dried at room temperature in front of a fan until their weight stabilized, then were baked in a dehydrator at 190°F to ensure the mycelium is fully inert. The initial drying stage was completed to mitigate potential cracking or deformation that drying at high temperatures can cause.

The V2 prototypes were made of two substrate combinations hydrated to 62.5% moisture content. The first dry substrate mixture was comprised of 40% hardwood sawdust, 40% soybean hulls, and 20% shredded hemp, while the second was comprised of 50% hardwood sawdust, 50% soybean hulls. All prototypes used *Ganoderma Lucidum* mycelium.

Molded parts for three luminary prototypes in molds.

Upper luminary component during demolding.

V2 + Secondary Coatings and Treatments

Prototype Treatments

The highest performing swatch treatments from the abstract investigation stage were applied to the luminary prototypes using similar methods to the previous swatch treatments. However, in pursuit of increased surface regularity, sanding and surface filling were added as processes to the shellac-based treatments. It was observed in a test done on scrap MBC of similar composition to the experimental models that the shellac coatings enabled the material to be sanded, and the resulting dust could be combined with additional shellac to form a wood filler-like paste that effectively filled undesirable surface irregularities. Previous experience with MBCs demonstrated that normally, sanding MBCs is difficult and unpredictable, especially when the substrate is heterogeneous in particle size or geometry. Thus, this treatment offers expanded opportunities to reveal novel surface manifestations of MBCs. Each luminary treatment, application process, and final photos are discussed in Table 7 at right.

Prototype before (left) and after (right) 2 coats of brushed on shellac.

Shellac paint prototype after initial coat of pigmented shellac (left) and first round of sanding (right).

Beeswax infusion prototype before (left) and after (right) infusion

Treatment	Process	Photo (room lights on)	Photo (room lights off)
Uncoated (control) A	N/A		
Shellac B	A thin coat of shellac was applied to all surfaces of the prototype. After drying overnight, the surfaces were sanded with 80 grit sandpaper. Sanding was halted when untreated surfaces were reached. Next, a paste made from the sanded dust and additional shellac was made and applied to surface pockets with a wooden spatula and by hand (while wearing protective nitrile gloves). A thin layer of shellac was applied over the filler to the entire model. It was again left to dry overnight before repeating the process. These three steps–sanding, filling, and coating–were repeated for a total of 4 times. The final two rounds were sanded with 120 grit sandpaper.		
Shellac paint C	Red pigment was mixed with shellac at an approximate ratio of 1:2 (pigment: shellac, by weight). Using this mixture, the initial application and sanding, filing, and coating steps described above were conducted.		
Beeswax infusion D	Beeswax was melted and the luminary pre-heated at 190°F in a dehydrator oven. Next, beeswax was applied heavily with a brush to all surfaces of the model. The model was then wrapped loosely in aluminum foil and placed back into the dehydrator. After 30 minutes, the surface-applied beeswax had absorbed throughout the material. A few bare spots were observed so the application and bake steps were repeated. The luminary weight was recorded before and after infusion to track the amount of beeswax used (63 g).		
Natural furniture polish E	Using a clean cotton cloth, the furniture polish was liberally applied to all surfaces of the model, ensuring the material was applied to both raised and recessed surfaces. The model was left to sit for 15 minutes before being buffed with a fresh clean cotton cloth to remove excess material.		

Table 7: Treatment processes and final photos of the coated luminary prototypes.

Consumer Survey

To assess preliminary consumer perceptions of the treated prototypes, 8 industrial design students, enrolled in an "Applied BioDesign" course in the School of Design at Virginia Tech, were surveyed. The questions asked, informed by the literature review, are below. A starting list of vocabulary (Figure 2) produced by Johnson et al. (2003) was provided to the students to contextualize the inquiry.

Questions:

Asked about all the luminary prototypes:

- Which prototype(s), if any, would you put in your home?

Asked of each prototype:

- What qualities of the material are appeal to you?
- What qualities of the material are unappealing to you?
- What qualities are missing or absent from the material that you'd like to see?
- What terms would you use to describe the material aesthetics? (Think about your 5 senses).
- What terms best describe your perception of the material? (Think about how the product makes you feel).

Aesthetics – **Sensory**	
Feel	Soft
	Hard
	Warm
	Cold
	Matte
	Textured
Form	Organic
	Angular
	Aerodynamic
	Industrial
Smell	Fresh
	Stale
	Natural
	Artificial
Colour	Transparent
	Translucent
	Opaque
	Reflective
Taste	Sweet
	Sour
	Salty
	Bitter
Sound	Muffled
	Ringing

Perception – **Symbolic**	
Aggressive	Passive
Cheap	Expensive
Classic	Trendy
Clean	Dirty
Clever	Silly
Common	Exclusive
Over-decorated	Minimal
Delicate	Rugged
Dull	Sexy
Elegant	Clumsy
Evil	Good
Feminine	Masculine
Formal	Informal
Friendly	Irritating
Functional	Useless
Futuristic	Historic
Handmade	Mass-produced
Honest	Deceptive
Humourous	Serious
Intricate	Plain
Mature	Youthful
Restrained	Extravagant
Temporary	Permanent
Weak	Strong

Figure 2: Vocabulary lists provided to survey participants, created by Johnson et al., 2002

Results

The consumer survey responses to questions asked of all prototypes yielded the results shown in Figure 3 They indicate that models B and C are viewed most favorably, while models D and E are viewed least favorably. The reported desirable qualities, undesirable qualities, and comparable materials for each prototype are shown in Table 8 where bolded phrases were repeated by multiple respondents.

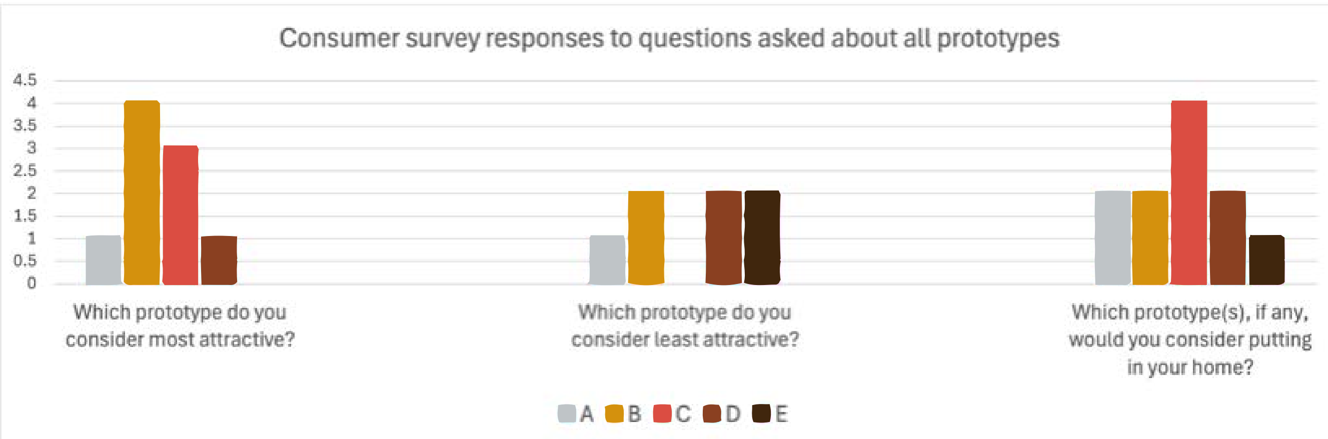


Figure 3: Prototype treatment evaluation consumer survey results

Model	Desirable qualities	Undesirable qualities	Comparable materials
A	**texture**, **consistent color**, natural **white color**, hard-looking	**unrefined**, **looks like mold/compost**, rough, too lightweight, sound	stucco, **popcorn ceiling**, **plaster**, drop ceiling tiles, foam, concrete
B	**color**, **visual texture**, **smooth finish**	**feels sticky**, too large aggregate, looks like OSB	**OSB**, **wood**, mulch, bamboo pieces
C	**uniform color, uniform finish, color choice,** cohesive, shiny	**color choice**, imitates other materials, **surface imperfections**	**plastic**, painted wood, clay, rubber, powder coated metal
D	matte, **good smell,** cohesive rough texture appearance	**inconsistent**, looks moldy, leave beeswax residue	**cork, MDF**, bark, rust
E	**visual texture, color**	unrefined, rough texture, yellowish, color	**cork**, gingerbread, adobe, dirt, carpet

Table 8: Compiled results from consumer survey feedback

On one hand, no treatment was viewed desirably by the majority of participants, suggesting that the treatments investigated are not sufficient to increase consumer desirability of MBCs. On the other hand, agreement between participants and reported differences between models indicates that the applied treatments convincingly altered consumer perception of MBCs, indicating that MBC appearance qualities may be significantly improved with further efforts.

Notably, good smell comprises 50% of the reported desirable qualities of model D, indicating that scent may be a valuable metric for future work. Additionally, consistency and inconsistency were two are the most highly reported positive and negative qualities respectively, emphasizing the importance of surface quality. Other related perceptions indicate that for smooth surfaces (models B and C), a high degree of perfection is required, but for textured surfaces (models A, D, and E), some mild variation is accepted.

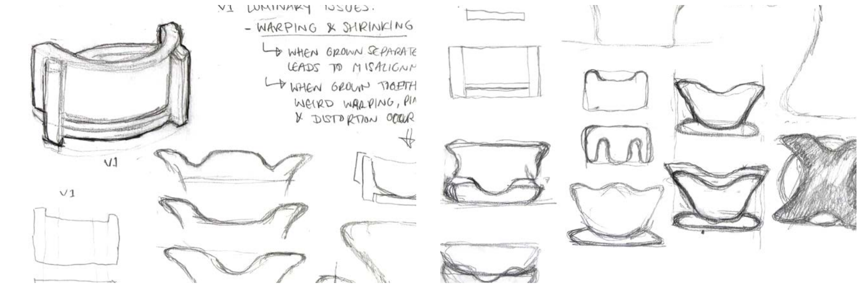
The substrate composition also affected the visual and tactile textures of the prototypes along with the degree of shrinking and warping. The hemp-inclusive mix displayed better dimensional stability while the hemp-omitting mix displayed more uniform texture. Both combinations, however, encountered issues during demolding and drying. Narrow sections occasionally broke during demolding, and even the most stable pieces warped and buckled in undesirable ways during drying. This revealed that, while an improvement over V1, V2 was not the most material-appropriate design.

Figure #: Images of V2 design faults. Aluminum foil spacer added to prototype during drying to mitigate unwanted warping (left), piece broken during demolding (middle), broken part being mended during the second growth stage (right).

V3

Redesign

Driven by experiences with V1 and V2, luminary V3 features a simplified assembly comprised of one mycelium component that readily affords demolding. By reducing mold complexity to two parts, the design affords both compression and in-mold shrinking, which will help mitigate unwanted warping and texture from occurring during drying.



Luminary V3 ideation sketches.

Luminary V3 rapid prototyping.

Final Design

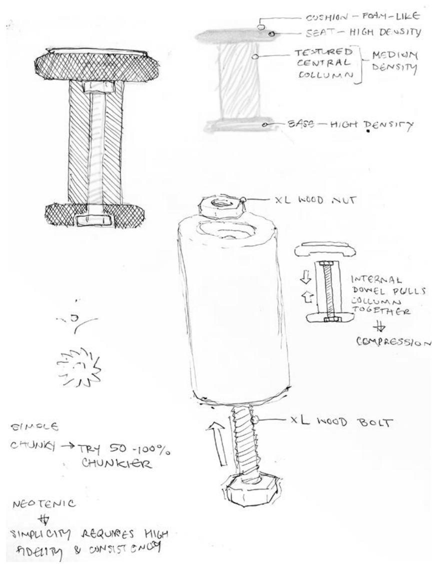
The final luminary design features a simplified assembly comprised of the mycelium-based body, a mycelium-based leather or SCOBY leather diffuser, and an LED panel. The diffuser connects to the body by locking into three narrow slots, making it easily removable to access the LEDs. This facilitates the separation of biological and technological materials, something critical within a circular economy. The form affords molding at a range of densities, increasing the CMF (color, material, and finish) possibilities.

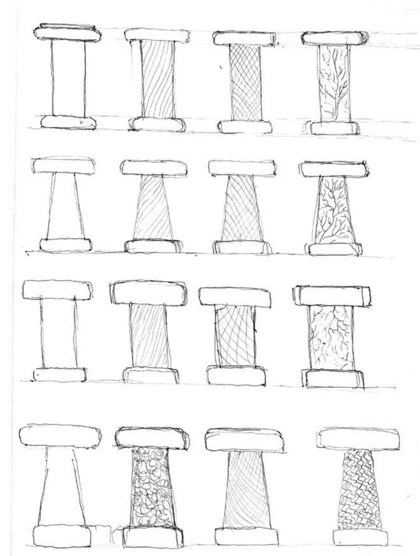
Stool

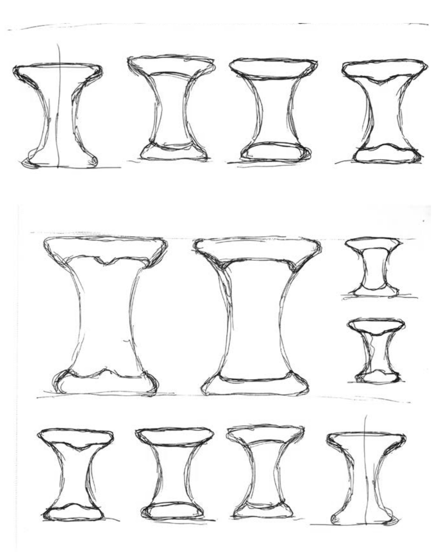
Ideation and Refinement

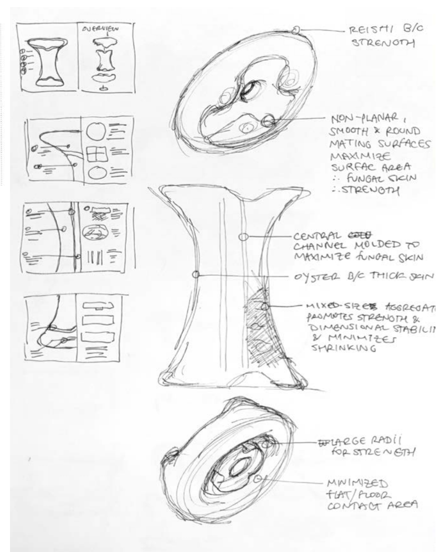
The ideation and refinement of the stool design was guided by the following criteria:

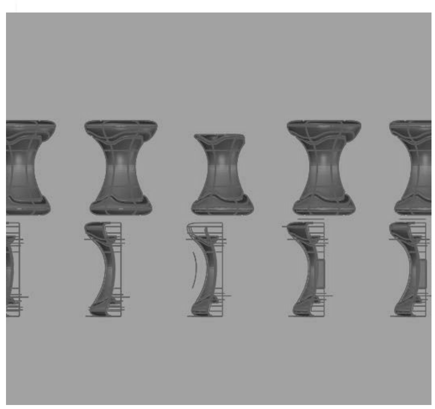
- Fully circular and compostable materiality
    - Upcycles waste streams
    - Circularity built-in
    - Repairable and maintainable
- Elevated & predictable material aesthetic expression
    - Textural consistency
    - Challenges MBC norms
    - Proposes new MBC semantics
- Exploits MBC demonstrated strengths
    - Compression strength
    - Fungal skin strength
    - Airflow maximization

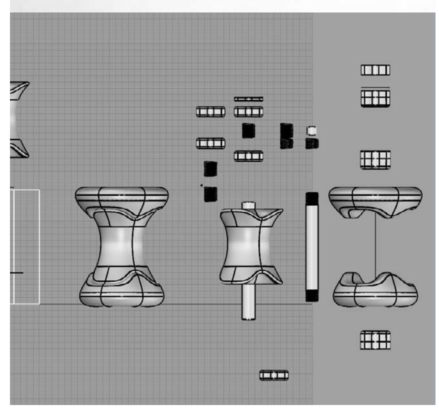








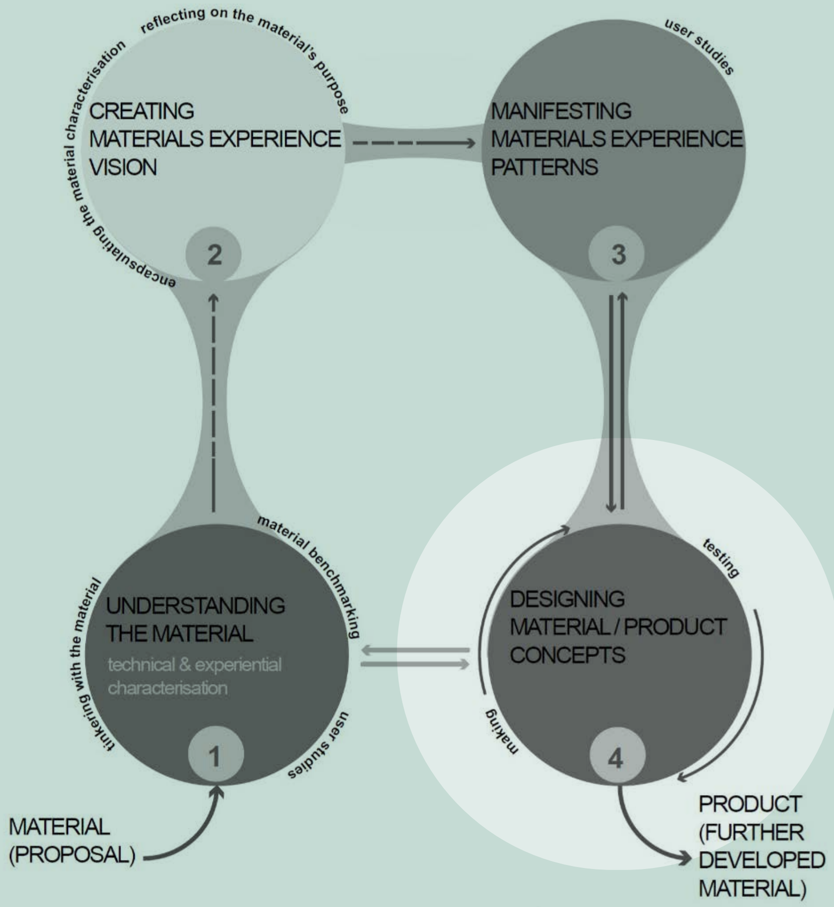




Scale Prototyping

Through scale prototyping, the following findings were discovered:

- Compression during drying improves cohesion and surface texture
- Shellac and shellawax treatments are effective
- Sanding treatments highly improved smoothness
- The modular design is viable



This stage of the work falls under phase four of material-driven design, designing material/ product concepts (Karana et al., 2015).

Applied MBC Case Study

Introduction

Building on the techniques, strategies, and design principles obtained during stages one and two, stage three is centered on designing material concepts from an MDD approach. The final stage of this thesis culminates in an applied MBC case study, the “Symbiosis Stool.”

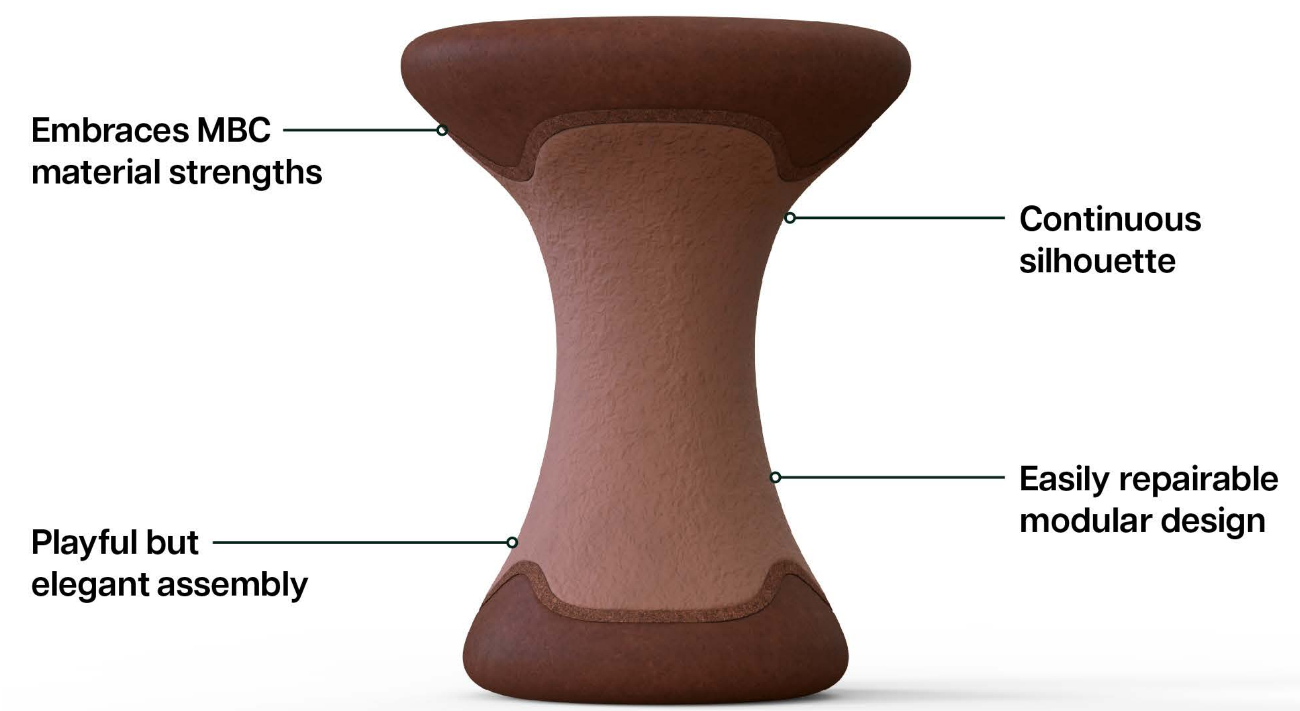
The Symbiosis Stool

The Symbiosis Stool

Overview

The mycelium-based stool demonstrates novel MBC material semantics and the viability of MBCs for certain furniture applications. Comprised of entirely compostable materials, with the potential for 100% waste stream material sourcing, the stool offers a highly circular furniture solution.

Molded production | **100% renewable & bio-based** | **Fully compostable**



Features

Embraces MBC strengths

Maximizes surface area of mating surfaces to maximize fungal skin.

Compressed assembly with central dowel.

Felt pads reduce acute stress to prevent brittle failure.

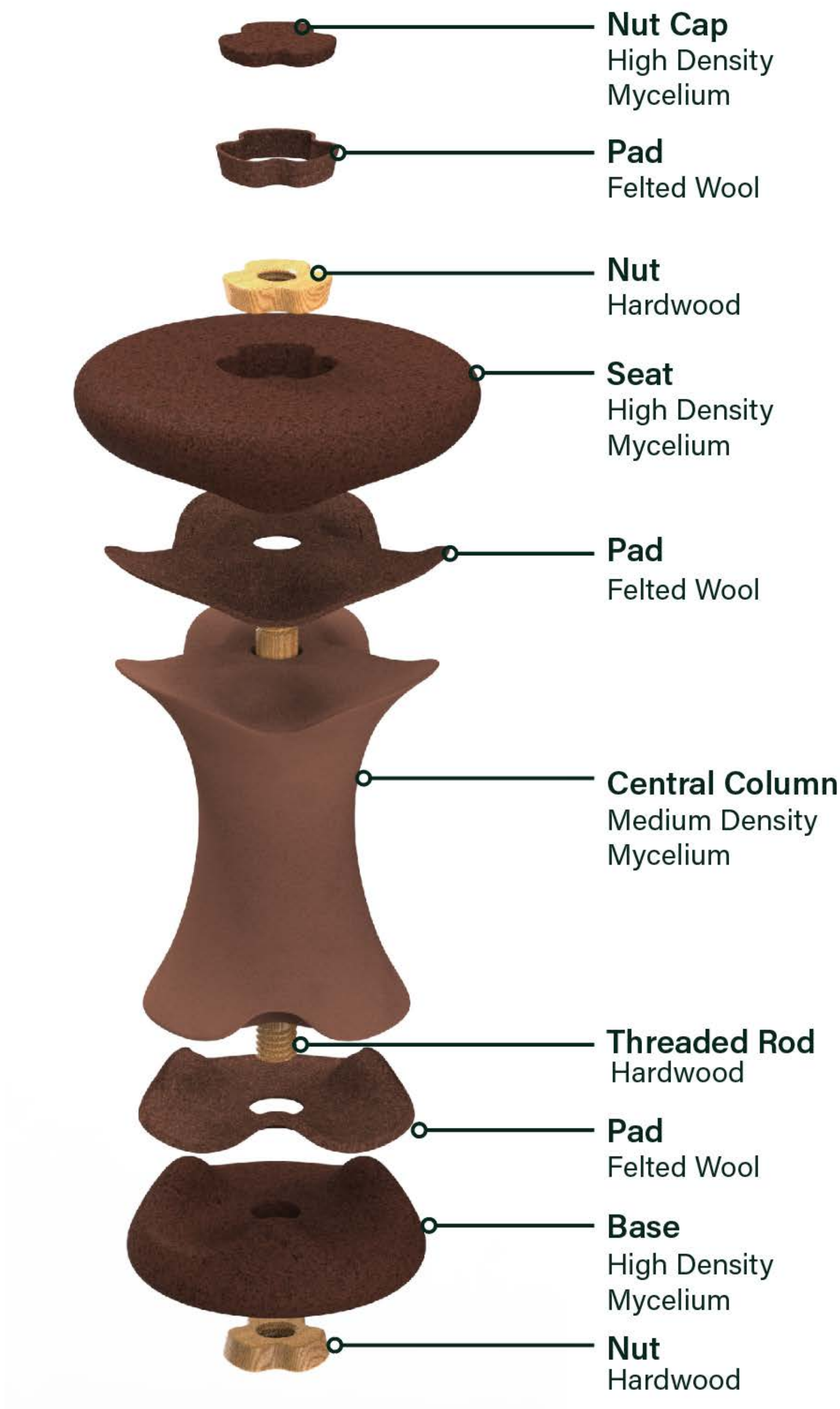
Formal Qualities

Clean, contemporary but playful silhouette.

Highly repairable and disassemblable

Adaptable CMF expressions possible

Assembly



Nut Cap
High Density
Mycelium
Pad
Felted Wool
Nut
Hardwood
Seat
High Density
Mycelium
Pad
Felted Wool
Central Column
Medium Density
Mycelium
Threaded Rod
Hardwood
Pad
Felted Wool
Base
High Density
Mycelium
Nut
Hardwood

MBC Composition

Seat & base

High density MBC

Core substrate:

50% hardwood sawdust,
50% soybean hulls

+

coconut coir
reinforcement fibers

***Ganoderma Lucidum*
(reishi) mycelium**

Shellac-based
translucent tint

Central body

Medium density MBC

Core substrate:

40% hardwood sawdust,
40% soybean hulls, 20%
finely shredded hemp hurd

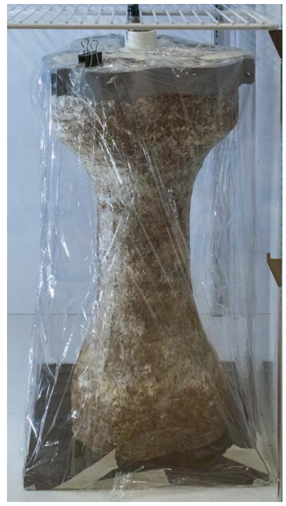
***Pleurotus Ostreatus*
(oyster) mycelium**

Shellac-based tint

Prototyping

Central Body

The cental body of the stool was molded in an 18-part 3D printed mold using PLA filament. Comprised of two main sections split radially in thirds. and three spacer sections, the mold design facilitated moderate levels of material densification. During compression, however, the mold failed in multiple locations, leaving approximately 1.5 inches of extra height on the final prototype body. Despite this complication, the molding procedure was effective. Increasing the wall thickness by 100-200% and adding verticle ribs is likely sufficient to achieve the desired degree of compression.



Molded body growing.

Mold failures during compression.

Body pre-compression.

Body post compression.

Body post baking.

Base and Seat

The base and seat of the stool were molded in two stages. First, 3D printed preforms were packed with mycelium spawn. The preforms are stretches to 200-300% of the final component heights to achieve material density once compressed. CNC-routed plywood forms sealed with shellac and lined with aluminum foil comprised the compression mold.
After the growth stage, the components were placed in their respective molds and compressed in a 20-ton hydraulic shop press. The modling process was effective and showed strong viability, espeically with a more robust setup. Fissures formed along the parting lines of each piece, more significantly in the seat. For this prototypes, voids and cracks were filled with a shellac and mycelium-based filler. This extra step, however, may be eliminated if the composites were hot pressed or baked under compression, neither of which were possible with the existing resource limitations.


Base and seat pre-forms.


Seat compression form.


Base post-pre from growth.


Base during compression.


Base post-compression.


Seat post-compression.

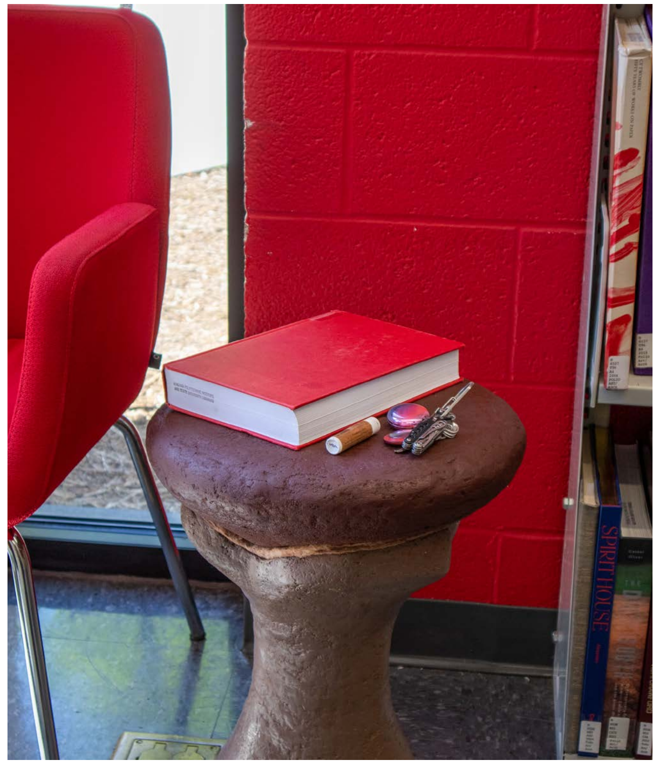

Seat and base post-baking.


Seat and base post-baking.


Base pre-filling.

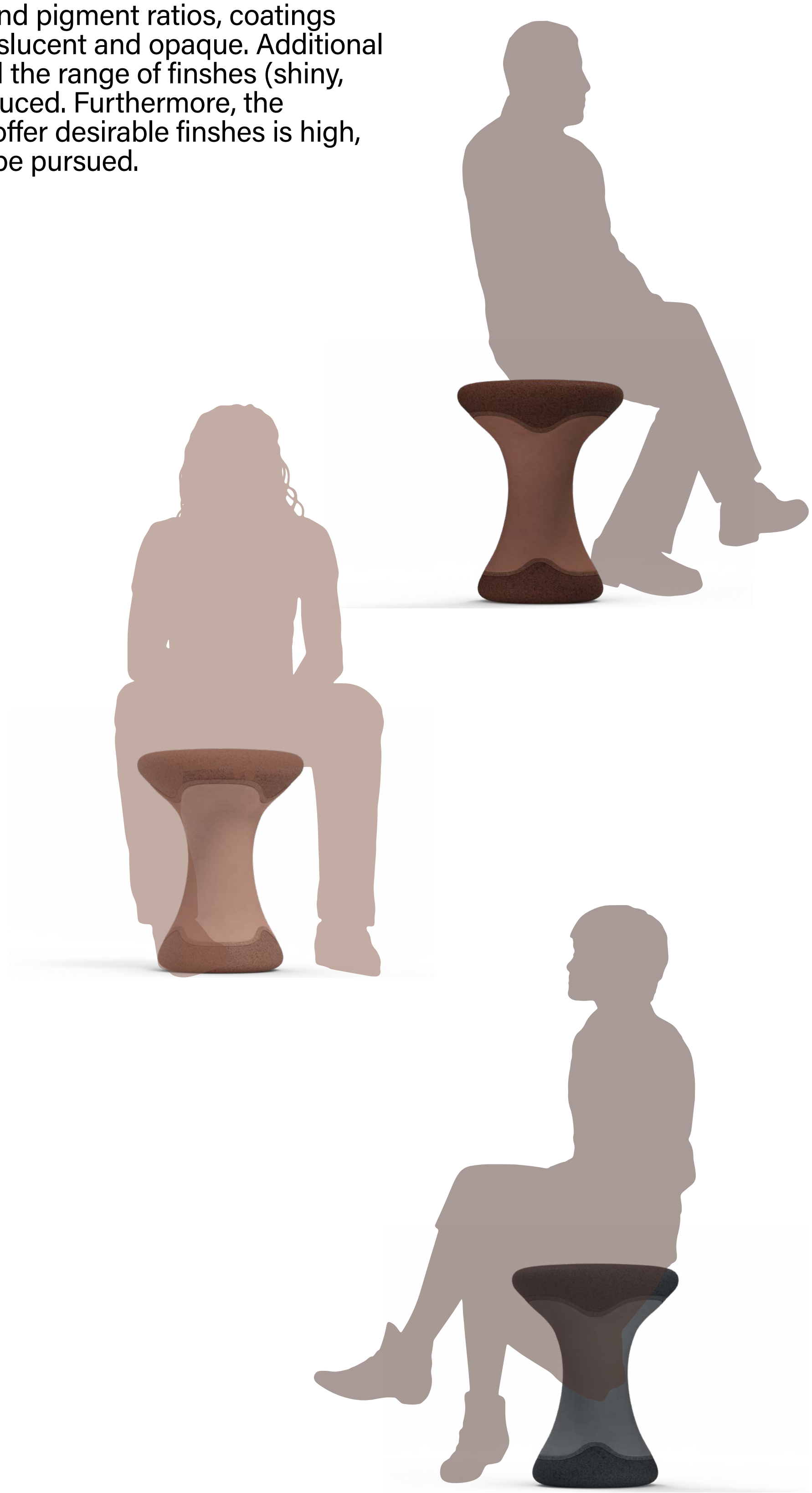

Seat post-filling.

Final Prototype



CMF Expression

The symbiosis stool is highly customizable in color and finish. Using various natural pigments and pigment ratios, coatings can vary from transparent to translucent and opaque. Additional efforts should be taken to expand the range of finshes (shiny, matte, eggshell) that can be produced. Furthermore, the potential of dyeing processes to offer desirable finshes is high, but underdeveloped and should be pursued.



Circularity

All components of the stool, including hardware and surface treatements, are biodegradable and home compostable.

Toledano for Getty Images

Comparing Footprints

To contextualize the symbiosis stool's environmental impact from a carbon emissions perspective, comparisons were made to concrete and recycled plastic. Using volumetric analysis and available data, the GWP of the stool was calculated, shown for each material below.

Mycelium

- Sequesters up to 1 kg CO2 per stool*
- Diverts waste streams
- No technosphere-biosphere contamination
- Renewable materials

Concrete

- Could produce 7 kg CO2 per stool**
- No recyclability or biodegradability
- Non-renewable material

Recycled Plastic

- Could produce 10-31.5 kg CO2 per stool***
- Plastic recycling creates extensive microplastic pollution (Bruggers, 2023)
- Downcycles materials
- Non-renewable material

* Based on Livne et al., 2022 finding that MBCs capture 39.5 kg CO2 Eq/m^3
** Based on data from Altshuler, 2020.
*** Based on data from Plastic Recyclers, 2020

Continued Efforts

There are many opportunities to build on this work, in pursuit of greater positive impact. The following topics have been identified as specific areas of focus with potential to contribute new knowledge:

- Robust environmental impact analyses
  - Consider mold and formwork materiality and production at scale
  - Consider lifecycle assessments (LCA) or techno-economic analyses (TEA) as starting points
- Create an agile material and procedural library
  - What substrates and species can be substituted to promote more localized production?
- Material research
  - Compression directionality
  - Longevity of coatings and composites
  - Biodegredation
- Further design optimization
  - Weight reduction and selective density optimization
  - Design for manufacturing
  - Greater CMF expression
- Additional Applications
  - Larger furniture
  - Toys and hobby materials
  - Architectural components
- Consumer desirability research
  - Expanded material perception inquiries
  - Treatments of furniture applications

Conclusions

Contribution

At large, these efforts are expected to contribute to the shift towards sustainability in the design and architectural industries, specifically from a circular and renewable sustainability perspective. By producing MBCs that can be readily integrated into the industry at an increased scale, this research will offer a viable renewable alternative to the linear, landfill-bound life that many products have, potentially revolutionizing the way materials and products are produced, consumed, and discarded.

Summary

Amidst a growing climate crisis, designers have a responsibility to care for the planet and its inhabitants. One way to exercise such care is by designing for a circular economy (Ellen MacArthur Foundation, 2022). Mycelium-based composites are unique and remarkable in many ways, one of which being their incredible alignment with CE principles. Sustainable, functional, and beautiful applications of MBCs for consumer products are out there, but they only scratch the surface of the material's potential.

Culminating in the design and full-scale prototype of a mycelium-based stool alongside the library of material swatches and samples produced, this thesis demonstrated that new MBC material semantics are possible. Furthermore, these new manifestations respond equally to consumer desirability, MBC material affordances, and application-specific requirements, highlighting the value of material-driven design in helping to bridge the gap between conceptual and practical MBC consumer desirability.

In nature, mycelium is the largely unseen powerhouse of ecosystems. Growing on dead plant matter, animal waste, plant roots, rocks, and more, the fungus feeds on "waste" as it nourishes itself (and sometimes other organisms too). What is trash to one organism is fuel for another, the underpinning concept of the circular economy. It is time to rethink current design and consumption practices and take lessons from nature. Both conceptually and practically, mycelium can help revolutionize materials and products within a circular economy and help build a healthier, more sustainable world.

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