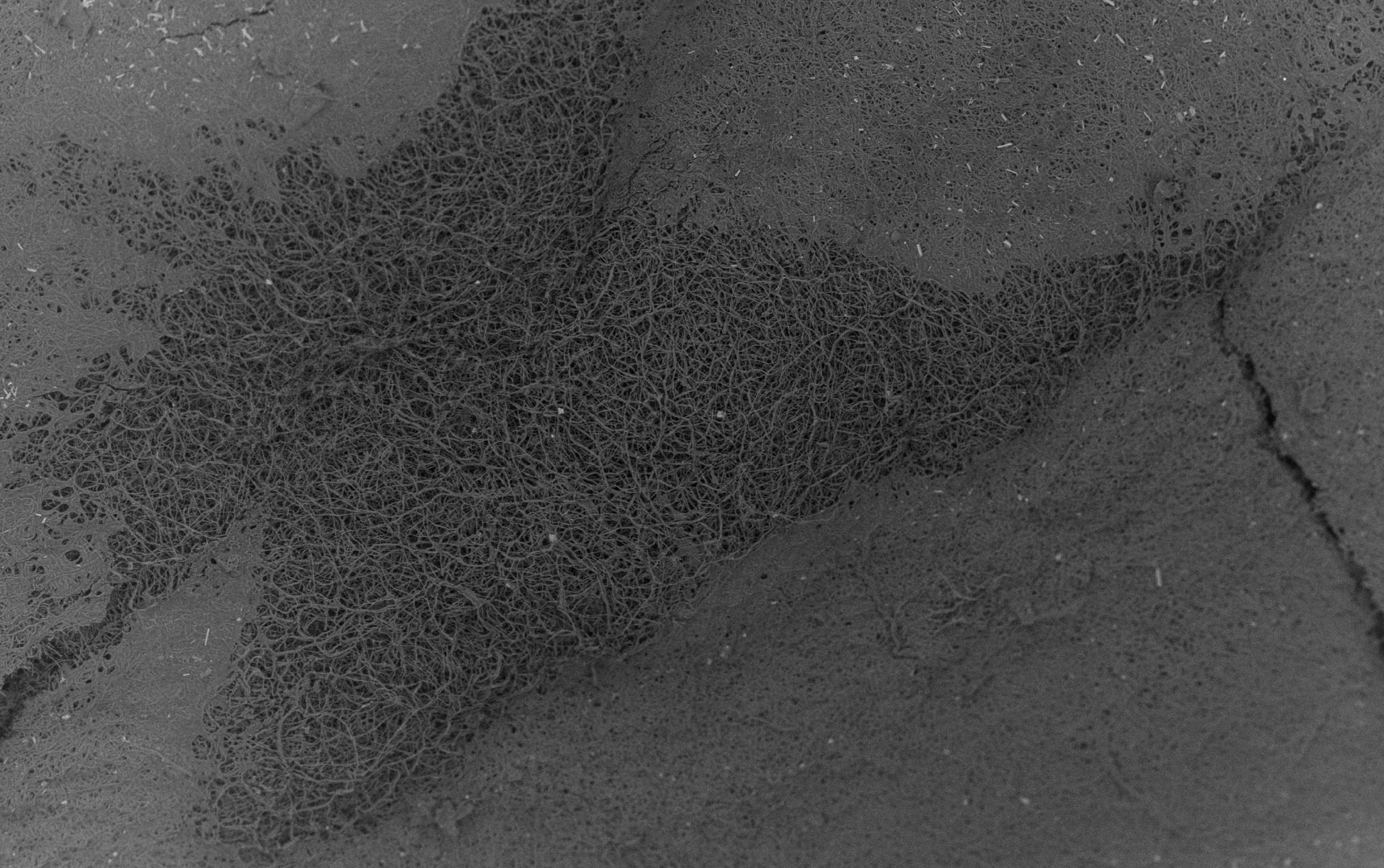


# Fungi in FLUX

Designing Regenerative Materials and  
Products with Mycelium

Arvind Bhallamudi





# Fungi in Flux

A thesis presented in partial fulfillment of the requirements for the Master of Industrial Design in the Department of Industrial Design of the Rhode Island School of Design, Providence, Rhode Island.

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Dedicated to my family,  
for Mom, Dad and Isha

# Contents

	<b>Acknowledgments</b>	12
	<b>Glossary</b>	14
	<b>Abstract</b>	16
	<b>A Note on Nature</b>	18
<b>1</b>	<b>Materiality and Waste</b>	23
	Living in the Anthropocene	25
	Navigating Ecological Complexity	31
	Surveying the Material Domain	41
	Nature's Answer to Waste	45
<b>2</b>	<b>Exploring Mycelium</b>	53
	Field Research at Narragansett	57
	Literature on Mycology	61
	Experiments and Design	69
	Bio-fabrication Methods	87
	Material Characterization	99
<b>3</b>	<b>Cultivating Myco-Products</b>	111
	Precedents in Bio-design	121
	An Alternate Approach to Prototyping	125
	Temporary Biodegradable Objects	137
	Organic Furniture for Future Spaces	149
<b>4</b>	<b>Fostering Systems</b>	165
	Flows and Mapping	169
	Life-cycle Assessment	178
	Concluding Thoughts	180
	Website and Exhibits	182
	<b>Bibliography</b>	186

## Acknowledgments

In the pages of this thesis on mycelium design, you will find not just my explorations and formulations, but more importantly the imprints of invaluable advice, feedback and ideas from remarkable individuals. This work stands on the shoulders of each of their contributions. Thank you all for being a part of this work.

I would like to thank the RISD Somerson Sustainability Innovation Fund, Marc Harrison Grant, Industrial Design Department, Edna Lawrence Nature Lab, CoWorks Research Lab, Brown Design Workshop and Hyundai Motor Group for supporting this project through various phases of development from 2021-2023. I'm also extremely grateful to Brown-RISD Innovation Community, Sol Koffler Gallery and Grad Exchange 2023 for providing this work a stage to share with the community.

I extend my gratitude to Jennifer Bissonnette for her unwavering wisdom and critique. Thank you for guiding me on multiple aspects, from developing experiments to analyzing findings towards tangible design.

Peter Yeadon, your expertise and knowledge in the realm of bio-design was extremely valuable and deeply inspiring. Thank you for teaching me how to think about materials and products across scales and systems for impact.

David Kim, Brynn Trusewicz and Ollie Rosario, working at CoWorks Lab for a year with your support meant the world to me. The materials prototypes in this research would not exist without these experiences and it has been a privilege to be part of the team.

To RISD faculty across departments and courses: Andy Law, Bill Foulkes, Peter Dean, Ayako Takase, Tim Maly, Patricia Johnson, Haley MacKeil and everyone else, your broad perspectives were enlightening and shaped this work to be its best. Thank you!

Shravan Rao, thank you for your unique perspective in creativity and technology. Discussing plans for interactions and experiences in emerging industries helped think at each stage of this work and was the backbone of this project.

Andreas Mershin, your energy was a driving force behind this thesis, helping navigate science, design and engineering through mycology. Thank you for a new lens to look at myco-materials at the edge of innovation.

Charlotte McCurdy, your focus on climate and design has been a compass since I started at RISD. Thank you for inspiring and encouraging me on this journey and for your insights in designing for wider audiences and bio-material futures.

Felipe Shibuya, Georgia Rhodes and Benedict Gagliardi, your extensive knowledge and expertise at the RISD Nature Lab was incredibly inspiring. Learning from you has synthesized my curiosity and passion for nature into bio-design work.

To the MID cohort, thank you for being an incredibly talented and supportive through our time together. Calgary Haines-Trautman, Isaiah Aladejobi, Maxwell Fertik, Haroon Waseem, Cynthia Lu - thank you for your constant feedback and ideas.

Vaishnavi Mehta, thank you for your multitude of ideas and critical advice in human-centered industrial design, visual thinking, material design, graphic design, storytelling, and for being an anchor through this journey.

Tom Weis, thank you for always challenging me to push the envelope in industrial design and green products: in form, function, fabrication and strategy. Your holistic advice shaped many of the critical decisions in this work.

Hillel O'Leary, your valuable insights for making this research creative and accessible were indispensable. From conception to exhibition, thank you for your support and accelerating this work through its most crucial phases.

To my thesis studio professors, Charlie Cannon and Ayako Maruyama, thank you for teaching me how to unravel wicked problems, extend my creativity through sketching and cultivate a meaningful narrative in my design process.

Nick Scappaticci, Christopher Maurer, Avantika Velho, Itika Gupta, Mark Araujo, Kennedy Liu, Daniel Rapoport, Emilia Mann, thank you for sharing your cognizant and practical insights that pivoted this research in a process that was anything but linear.

To my friends, Jared Mompoin, Rini Singhi, Prateek Shankar, Harshal Duddalwar, Priyata Bosamia, Shivani Pinapotu, Srikar Hari and everyone else - thank you for your constant support and your stream of perspectives across disciplines.

## Glossary

**Anthropocene:** Era marked by significant human impact on Earth's ecosystems.

**Accessibility:** Ensuring equal access to resources and opportunities.

**Bio-design:** Design methodology integrating biology and design principles.

**Bio-materials:** Materials derived from, or enabled by living organisms.

**Closed-loop:** Systems where waste is used as an input resource.

**Circular Economy:** Economic system prioritizing reduction, reuse, and recycling.

**Efficiency:** Maximizing output while minimizing resource use.

**Ecology:** How organisms relate to each other and their physical surroundings.

**Ecosystem:** A community of organisms interacting with their environment.

**Material Ecology:** Study of materials and their ecological impact.

**Material-driven:** Approaches prioritizing material properties and characteristics.

**Mycelium:** The vegetative part of a fungus, consisting of a network of filaments.

**Mycology:** The scientific study of fungi.

**Myco-products:** Products derived from mycelium or other fungal components.

**Regenerative:** Systems that restore, renew or revitalize their resources.

**Resilience:** The ability to recover quickly from difficulties.

**Sustainability:** Meeting present needs without compromising future generations.

## Abstract

As the world grapples with the escalating crisis of climate threats and environmental degradation, this thesis delves into the synergistic potential of design and biology by developing a life-centered approach to industrial design. Harnessing the power of a unique organism, Fungi, the study proposes an accessible, efficient, and resilient material system.

This research aims to utilize local waste streams to create mycelium-bound structures, functional materials, and products. An experimental, small-scale, carbon-negative bio-fabrication protocol is modeled by developing mono-tubs, grow-tents and bio-printing methods. The materials' performance qualities are evaluated through comparative mechanical testing and survey of experiential attributes. Workshops introduced participants to the creative possibilities of integrating myco-materials into prototypes, leading to the conceptualization of biodegradable objects and furniture.

The work tested the feasibility of waste transformation with mycelium. To foster a deeper understanding of the value of resources, the life-cycle, carbon footprint and impact of these materials were also examined. The formulations and strategies from the study are shared through exhibits, talks and a website to make it more accessible to the community and beyond.

Envisioning a paradigm shift in industrial ecology, the proposed solutions reduce dependence on non-biodegradable, toxic, and harmful materials. The study advocates a heterogeneous system that uses biodesign engagement and engineering technology to treat waste as a resource and prolong the lifespan of materials and products. Embracing the principles of nature and biological circularity, this thesis hopes to transcend the trajectory of conventional materials and illuminate the path toward a regenerative future.

**Keywords:** Material Ecology, Mycelium, Biofabrication, Regenerative Design

## A Note on Nature



Photographs taken at Sanjay Gandhi National Park and Bannerghatta National Park, India.

Drawing on my interests in wildlife photography, I immersed myself in bio-design while working at the Nature Lab during my first year in the RISD grad program. Here, I revisited core principles of physics, chemistry, and biology while experimenting with synthesizing biodegradable materials. As I conducted bio-material workshops, trainings and consulted with students, I honed my skills in transforming fungi and algae into materials with diverse properties. My fascination with the natural world led me to spend more time in the microscopy lab, observing minute wonders and studying fossils at the natural history collection.

In prehistoric times, stargazing and celestial mapping served as a unifying language, a connection that we have lost as modern city dwellers obscured by light and noise. The vastness and intricacy of nature, spanning from microscopic organisms to cosmic bodies, evoke a profound sense of wonder and humility. As I ponder the underlying patterns of the universe, I reflect on my engineering background, where I learned about chaos theory and its unpredictability.

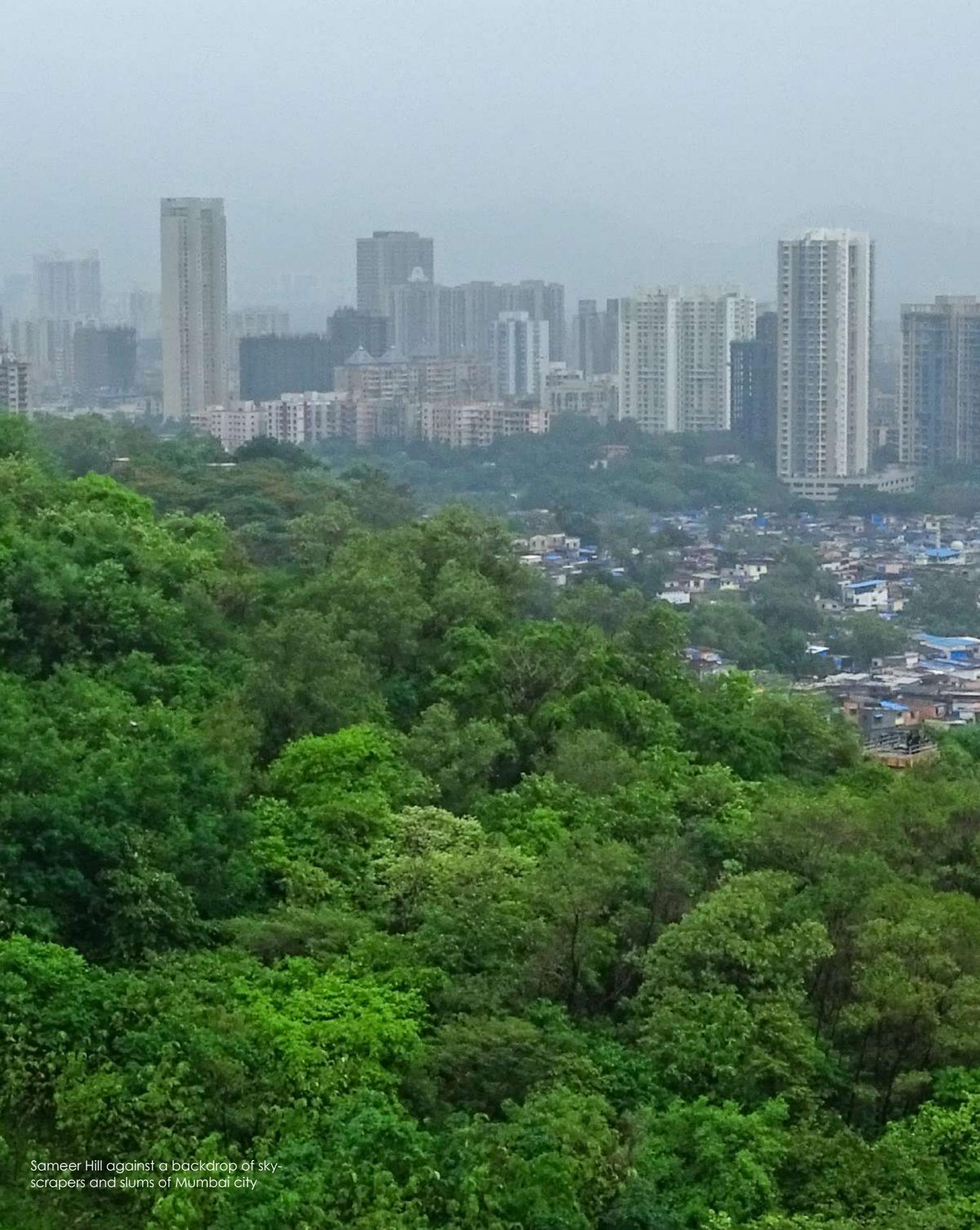
At the same time, we recognize and utilize many natural patterns such as the golden ratio and fractal geometries that allow our designs to be more effective and efficient. Ancient organisms that predate human existence, such as algae, fungi, and bacteria, have had millions of years to evolve, adapt, and develop life-sustaining strategies. Algae, dating back to the Precambrian period around 3 billion years ago, withstands extreme temperatures, while fungi have mastered the ability to break down toxic substances and remediate radioactive materials. Working with these ancient life forms can offer valuable insights into their survival mechanisms, revealing information about forms, processes, and ecosystems that can benefit us.

Emulating nature has been an intrinsic part of humanity for ages, and now that it has materialized into formal practices such as biomimicry, we can accelerate learning, extend collaboration and redefine coexistence with nature.



PART ONE

# Materiality and Waste



Sameer Hill against a backdrop of skyscrapers and slums of Mumbai city

## Living in the Anthropocene

The Anthropocene describes the current geological epoch in which human influence has become the dominant force affecting Earth's ecosystems. Natural processes like volcanic eruptions, meteor impacts, and shifting tectonic plates have always contributed to changes in Earth's climate. The Younger Dryas event, which marked the end of the last Ice Age, exemplifies the planet's vulnerability to sudden climatic shifts.

Today, however, human activities rather than natural cycles such as burning fossil fuels, extracting materials, and modifying landscapes, primarily drives climate change at an alarming and unprecedented rate. Elizabeth Kolbert, in her book "The Sixth Extinction: An Unnatural History," emphasizes that the current rate of species extinction is a direct result of human activity, leading to a massive biodiversity crisis.

Amitav Ghosh, in 'The Great Derangement: Climate Change and the Unthinkable', explores our collective denial of climate change and the Anthropocene, leaving us unprepared to address their challenges. Rising global temperatures impact ecosystems and species, with melting ice caps and glaciers causing sea levels to rise and threatening coastal communities and habitats. Ocean acidification, resulting from carbon dioxide absorption, endangers marine ecosystems and countless species. Deforestation and habitat destruction further exacerbate biodiversity loss, pushing many species to extinction. These actions and effects have disrupted the delicate ecological balance that evolved over millennia, leading to ecosystem collapse and resource decline. Many communities face increasing vulnerability to repercussions such as food and water scarcity, loss of arable land, natural disasters, and disease spread.



Trash and cyanobacteria in stagnant water  
at Gano Park, Providence RI



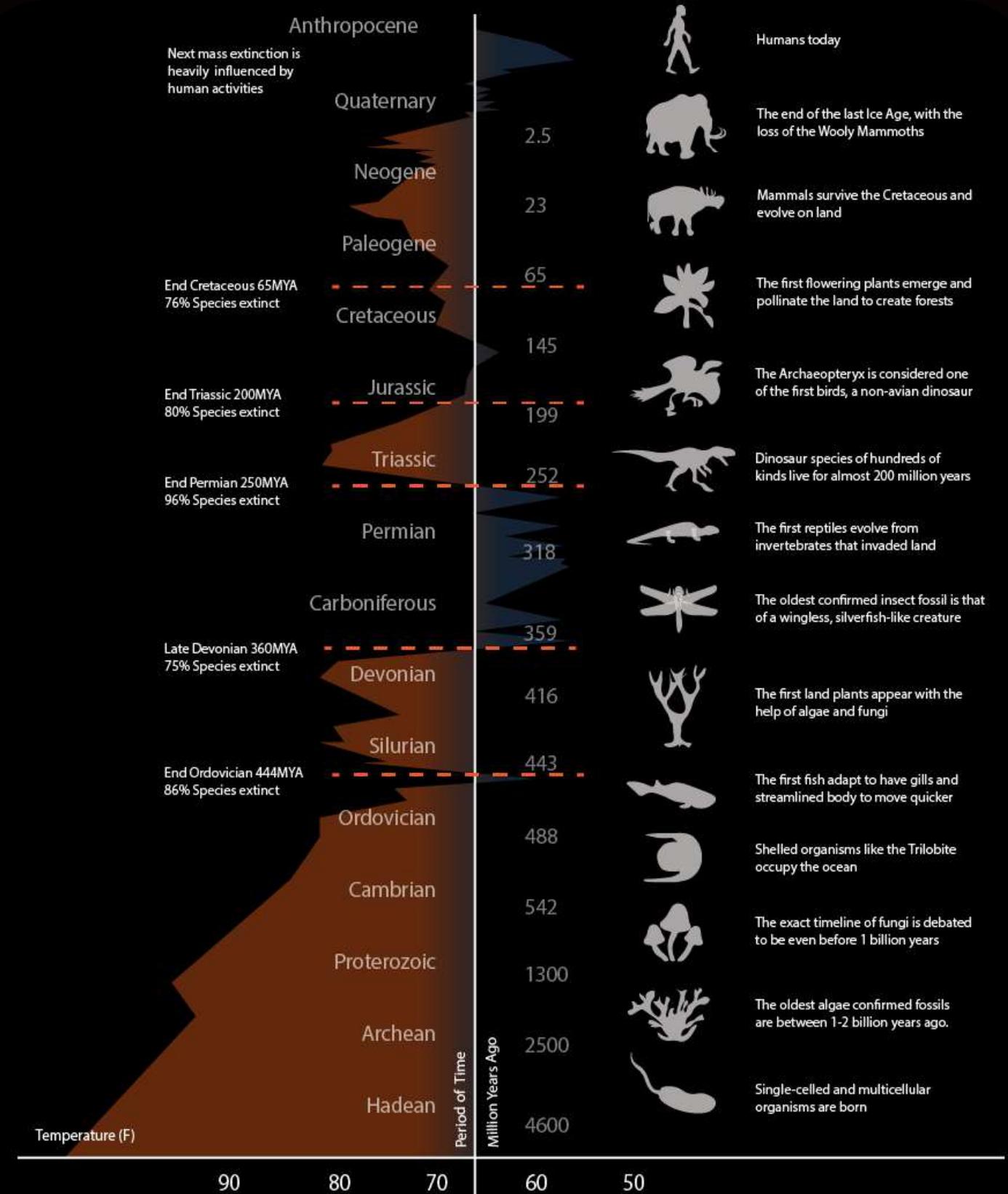
Polluted and clogged sewage  
canal in Andheri, India.

# Climate Fragility

Our insatiable demand for resources and unsustainable consumption patterns push the planet to its limits, endangering life on Earth. As ecosystems get disrupted and the biosphere's resilience weakens, there are irreversible consequences jeopardizing our well-being. In "This Changes Everything: Capitalism vs. The Climate," Naomi Klein argues that our current economic system perpetuates environmental destruction and undermines climate change mitigation efforts. The interconnected nature of human and ecological systems is undeniable, and the exploitation of natural resources and the relentless pursuit of economic growth have driven our planet to tipping points.

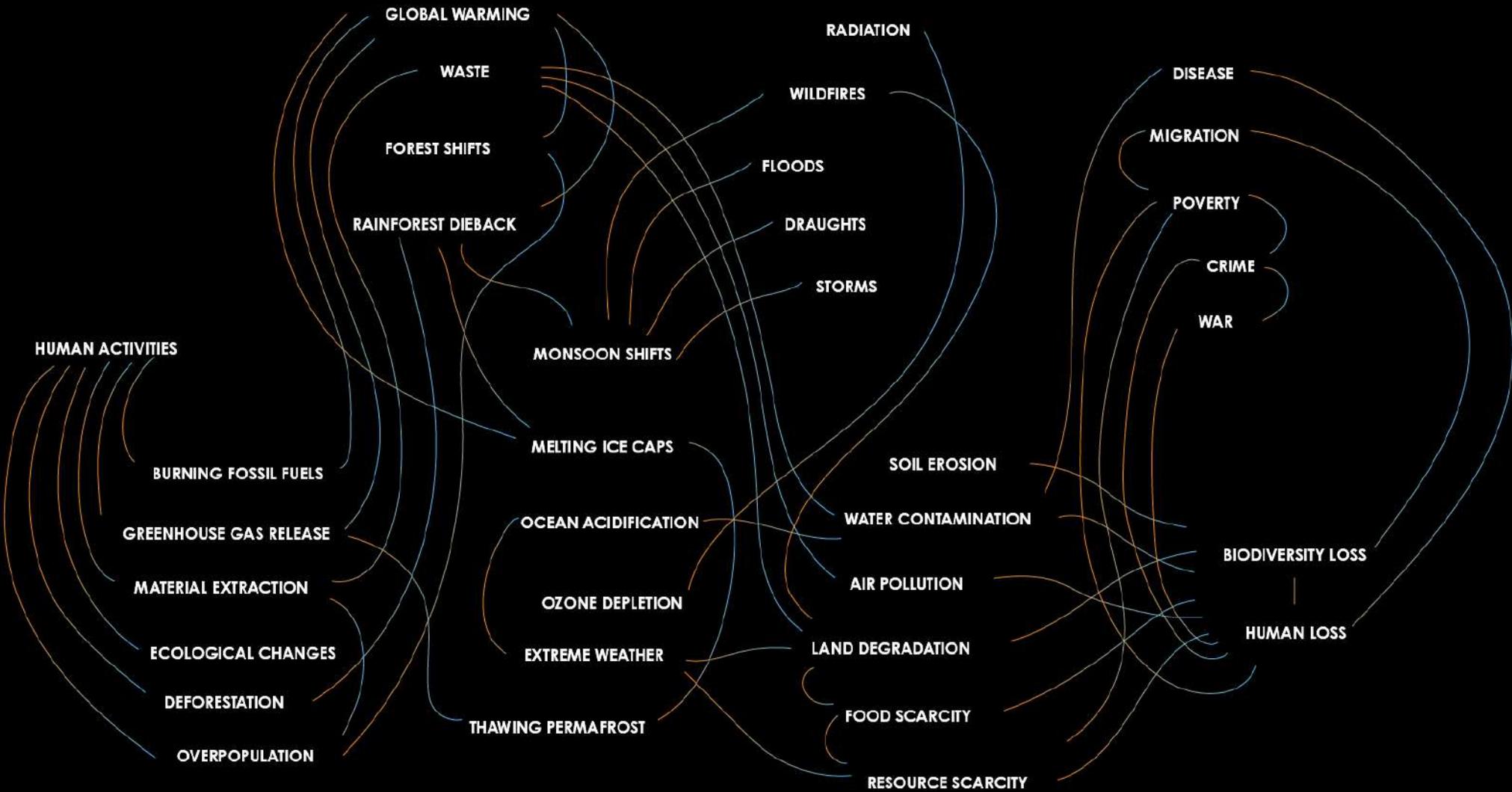
By combining data from ice cores about temperature against geological time and various animal evolution milestones, we can visualize the planet's temperature variability and notice how periods of high global temperatures correlate to mass extinctions.

Reimagining our relationship with nature and acknowledging our responsibility as stewards of the Earth, we can begin to forge a new path that respects the delicate balance of our world and ensures a viable, thriving future for generations to come. Living in the Anthropocene recognizes the gravity of our impact on the planet to take action and mitigate the consequences.



Adapted from Smithsonian Institution and Britannica Encyclopedia

# Navigating Ecological Complexity



Ecological systems, the intricate web of connections and interactions between living organisms and their environment, are critical to our planet's life-support mechanism. As human activities continue to grow and intensify, we are witnessing a concerning trend of widespread environmental degradation and ecosystem disruption. Striking a balance between emulating nature's design principles and navigating ecological complexity is a formidable task.

Numerous frameworks and theories have been developed to address the challenges posed by ecological complexity, in books such as systems-oriented: *Natural Capitalism and Biomimicry*; ontology-oriented: *Vibrant Matter and Design for the Pluriverse*; material-oriented: *Neri Oxman's Material Ecology*; and footprint-oriented: *Ellen McArthur Foundation, UNEP, Drawdown* and countless more.

A rough mindmap of ecological complexity and interconnected effects for humankind



Exploring biomimicry at the RISD Nature Lab by abstracting the gait and movement of starfish bio-mechanics

Natural Capitalism, a book by Paul Hawken, Amory Lovins, and L. Hunter Lovins, introduces a new economic model that emphasizes the value of natural resources and ecosystem services, which form the framework for Natural Capital.

**Radical resource productivity:**

This strategy focuses on dramatically improving the efficiency with which resources get used, leading to reduced resource consumption and minimized waste, forming the basis of a circular economy. It also promotes the idea of frugality and “doing more with less.” From a designer’s perspective, it highlights an opportunity to devise innovative methods for process design. However, it poses a challenge of overcoming traditional design methods and demands significant investigation in research and technology to ensure responsible and measurable efficiency.

**Service and flow economy:**

Businesses function by leasing products or offering services, fostering longer-lasting and more efficient products. This model incentivizes companies to minimize resource use and waste while meeting customer needs. It requires a shift in the consumer mindset from ownership to users, and businesses need to develop sustainable models to implement this strategy profitably.

**Biomimicry:**

Biomimicry is learning from and emulating nature’s forms, processes, and ecosystems. By studying these systems, we can apply principles to our designs, creating solutions that are conducive to life and the environment. It offers a vast scope for designers to draw inspiration from nature’s proven designs, potentially leading to more sustainable and harmonious solutions for our environment. The challenge lies in successfully interpreting and translating these intricate biological systems into feasible design solutions.

**Investing in natural capital:**

This aspect acknowledges the value of ecosystem services and supports practices that maintain or improve these, such as regenerative agriculture, habitat restoration, and conservation efforts. Recognizing the inherent value of natural resources is an opportunity and a responsibility to design products and systems that conserve and enhance natural capital. Nevertheless, this requires a fundamental change in how we value and account for natural resources, driven by the inertia of traditional economic systems.

In another study of Vibrant Matter by Jane Bennett, the work delves into the concept of “vital materialism.” It encourages reevaluating the role of non-human, inanimate objects in our world. The book focuses on the agency of material objects in shaping the world. It explores the idea that all matter, whether living or nonliving, possesses a form of agency and vitality that influences our environment and experiences—Bennett’s philosophies and strategies center on rethinking human interactions and materialism.

**The political ecology of things:**

By considering this agency and vitality, we can develop a more inclusive political ecology that respects the power of material forces and the interconnectedness of all elements in our world. This perspective extends the design responsibility beyond human-centrism towards a consideration of all entities in the design process. It implies the need to overcome the deeply ingrained anthropocentric approach to design and the adoption of new metrics to evaluate design impacts.

**The vitality of matter:**

Bennett proposes that matter has a form of life, energy, or vibrancy, which influences its interactions with other entities. Recognizing this vibrancy can help us better understand the complex interplay between human and non-human elements. The inherent life force in materials can open new avenues in designing for this unseen energy.

**Distributed agency:**

The idea is that agency is not exclusive to humans or living organisms but that all material entities share it in a complex web of interdependencies. It acknowledges the impact of non-human forces on our world. The agency of all material entities allows designers to think about design beyond human use, considering how a product interacts with the wider ecosystem. This holistic view could lead to more sustainable design outcomes but also presents the barrier of predicting and controlling these broader, interconnected impacts.



A studio project on biomaterials investigated local seaweed collection, processing and synthesis into packaging materials

In addition, programs from UNEP, Drawdown, McArthur Foundation, Cradle to Cradle, and Biofabricate have developed sustainability frameworks to guide our understanding and actions toward a more sustainable future. Concentrating on waste reduction and recycling, the circular economy approach proposed in many frameworks aims to create more efficient and sustainable resource management. These concepts are in stark contrast to the linear models of material infrastructure. While numerous climate solutions are emerging based on the language and vocabulary of these sustainability frameworks, such as a circular economy, it is crucial to distinguish between truly sustainable options and green washed alternatives.

In a circular economy model, materials and resources go through reuse, repair, re-manufacturing, and recycling through various strategies. This goes to the point that this industrially-circular approach often overlooks the eventual end-of-life for materials. After multiple cycles, these materials may become unusable or lost, creating waste that ultimately harms the environment. Additionally, the quality of materials diminishes in each cycle, and the collection and distribution of these materials become elongated and costly for organizations. There is a need for a model that goes beyond recycling systems and constantly considers materials to change and transform with ecological cycles.

**Material Sourcing:** Sustainably sourced and ethically produced materials to minimize environmental and social impact.

**Material Health:** Non-toxic, bio-degradable materials that minimize the risk to people and the environment.

**Energy Efficiency:** Minimize energy consumption during material production, transportation, and usage.

**Water Stewardship:** Implement water-saving measures throughout the product life cycle and protect water resources.

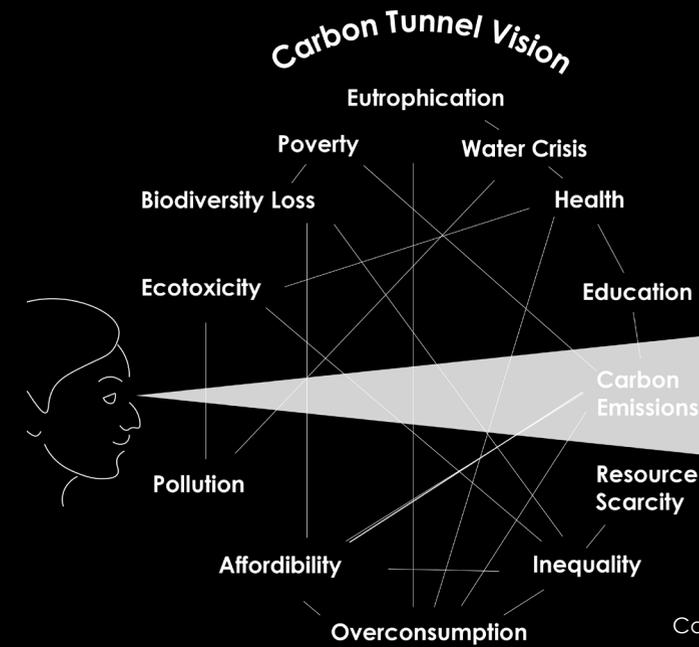
**Emissions Management:** Monitor and minimize emissions and pollution from extraction, production, transportation, usage, and disposal.

**Resource Conservation:** Encourage the efficient use of natural resources and raw materials, reducing the overall demand for virgin materials.

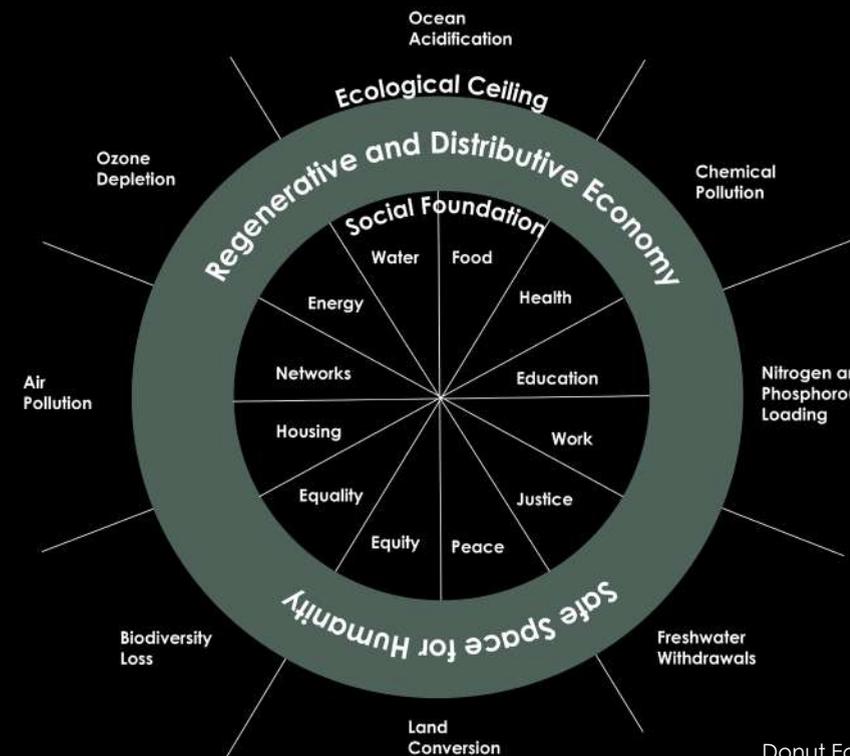
**Circular Design:** Adopt design principles that enable the reuse, repair, and recycling of products and materials, prolonging their life and reducing waste.

**Social Responsibility:** Ensure fair labor practices and equitable access to resources and opportunities.

**Continuous Improvement:** Regularly evaluate and update sustainable design practices to incorporate new technologies and best practices for holistic benefits.



Carbon Tunnel Vision and Sustainability Transition diagram adapted from Jan Konietzko



Donut Economics and the sweet spot for humanity, adapted from Kate Raworth

# Resource Ecology Design

To condense a set of design principles, the author contacted domain experts in biology, design, engineering, academia, and business to understand sustainability perspectives, unravel jargon, and discover the methods essential for a more sustainable design.

During one interview with Itika Gupta, founder of DungSe Labs, the importance of sustainability in ecological and financial viability was brought up. She emphasized, "A resilient system needs to adapt to different situations, ensuring its flexibility for enduring and prospering in a rapidly changing world."

In another interview with Avantika Velho, designer at TerreformOne, the meaning of resilience is again used in conjunction with sustainability, further highlighting the need to be cognizant of the ecosystem surrounding any intervention, "Designing with resilience for the ecosystem in mind ensures that every decision considers the long-term outcomes and the interconnectedness of all aspects of the environment."

Charlotte McCurdy, creator of 'After Ancient Sunlight' and faculty at Arizona State University, spoke about the value of building local ecosystems while recognizing the importance of exchanging ideas, knowledge, and resources between diverse stakeholders. She mentions, "A sustainable material system would internalize its externalities, accounting for environmental, economic, and socio-cultural costs throughout the life cycle of materials."

Mark Araujo, a research fellow at Boston Urban Mechanics, highlighted the concept of a circular and fair economy. The discussion centered on disseminating knowledge, funding, and recognition to areas frequently undervalued in society. Meanwhile, Professor Andy Law from Rhode Island School of Design stressed the significance of inexpensive solutions in generating new markets and prospects to disrupt conventional economic models. He also mentions how the life-cycle of resources needs to be carefully examined and quantified in relation to its alternative contexts.

Three values emerged from common themes across the various discussions, reflecting the essential qualities needed to address ecological complexity and create a sustainable future. They encapsulate the essence of these diverse frameworks and theories.

**Resilience:** To create resilient systems, we must focus on their ability to adapt and evolve in changing circumstances.

**Efficiency:** Efficiency is essential to maximize the use of resources and minimize waste through optimization.

**Access:** Access ensures diverse populations benefit from and contribute to knowledge and development.

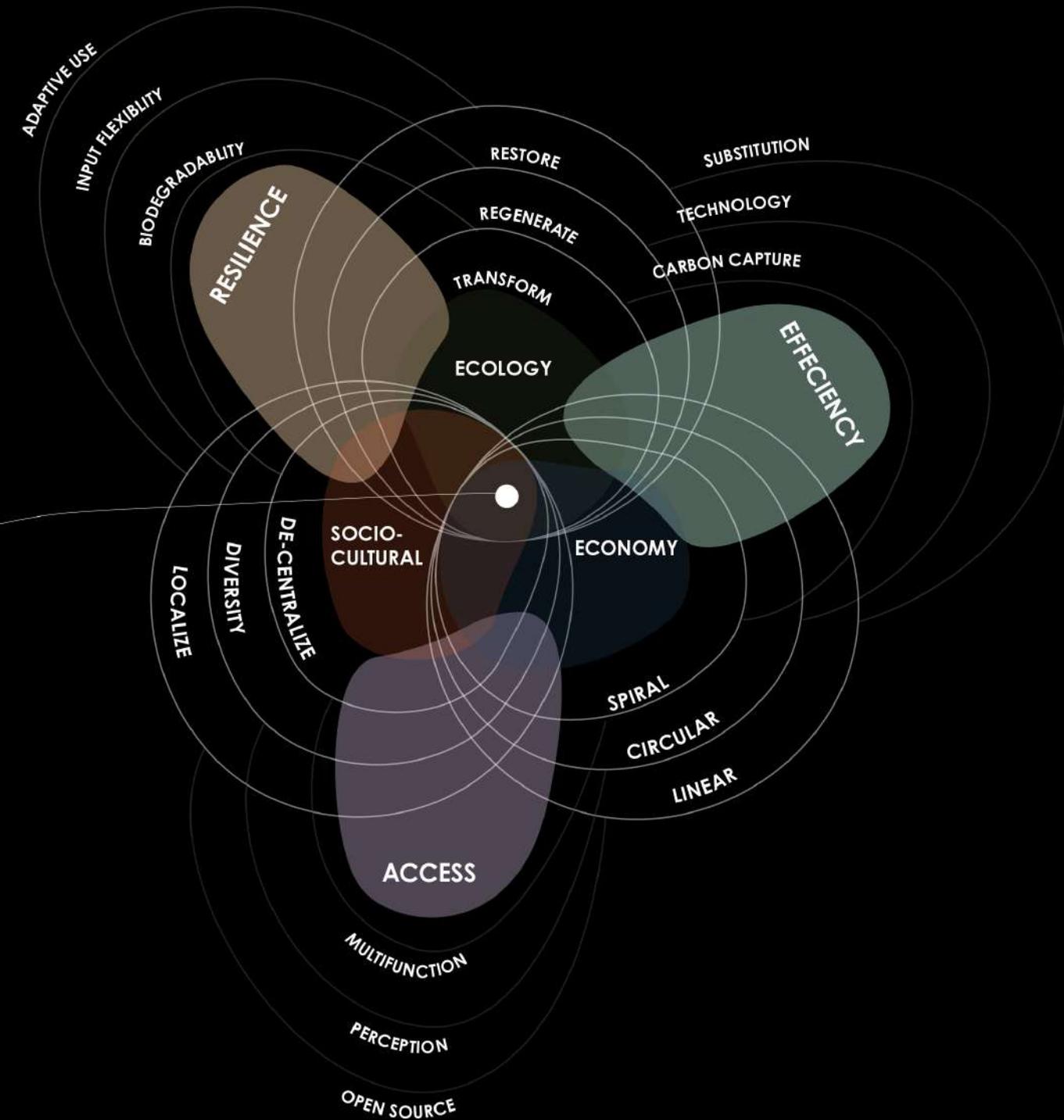
The identified values are a bedrock for effectively addressing ecological complexity's intricacies and ensuring that our designs and interventions contribute to human and ecological systems' overall health and well-being. These discussions and insights resulted in a comprehensive map depicting three intersecting spheres representing the fundamental domains that converge upon the material nature of systems. This visual representation vividly captures the intricate connections and relationships established between these domains, providing a design framework for implementing sustainable practices.

## MATERIAL

Emulating evolutionary strategies of nature, we can design biologically-centered resource solutions. A resilient, efficient and accessible approach is needed to re-establish an equilibrium between human activities and the natural world.

## DESIGN

Investigating the nature of materials and complexities of socio-economic-ecological systems, new modes of materiality emerge. It brings an opportunity to positively engage individual and community-based practices with life-centered design.



Material Nature Design is a visual framework that situates our physical and material reality at the core of fundamental systems and finds connections and opportunities for sustainable futures.

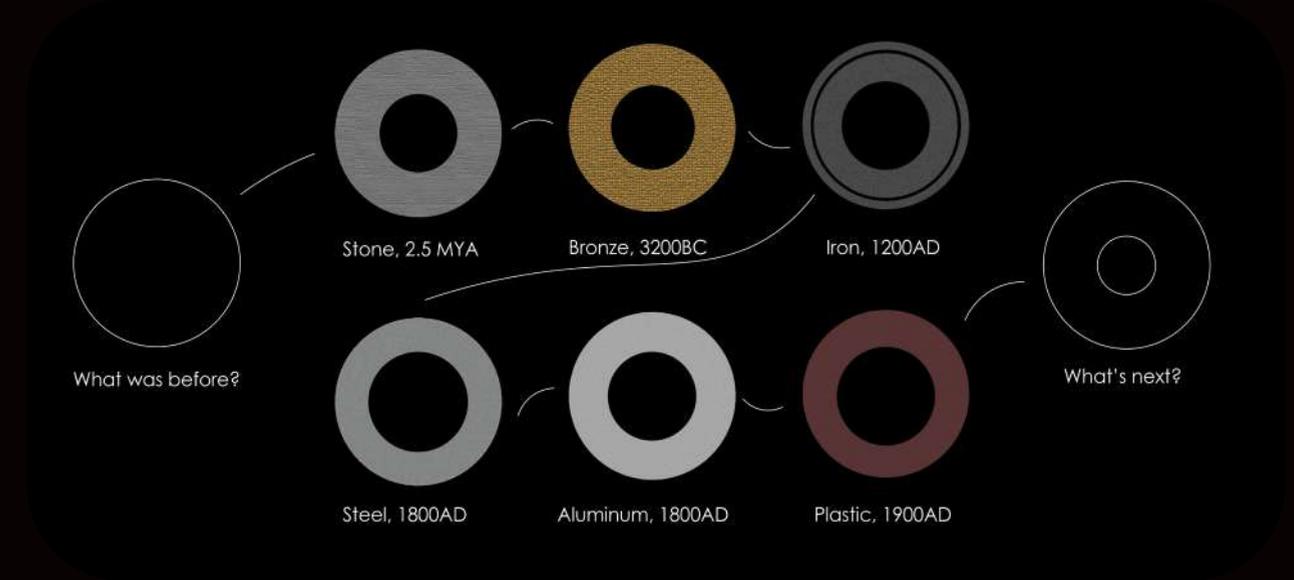


A heap of discarded vehicle tires at the Rhode Island Resource Recovery Center

## Surveying the Material Domain

Materials have been the cornerstone of human progress throughout history, shaping our evolution from the stone age to the present era of advanced technologies like bio-materials and 3D printing. For instance, the wheel has been iterated and innovated for millions of years through a range of materials, geometries, and fabrication processes, embracing ecological systems requires us to look beyond the linear, reductionist approach that has defined much of human progress and accelerated since the last industrial revolution. This model has led to an alarming increase in global material extraction, which reached 92 billion tonnes in 2017, a 254% growth since 1970 (International Resource Panel).

Moreover, the world generates 2.01 billion tons of municipal solid waste annually, with at least one-third of that not managed in an environmentally safe manner (World Bank). By 2050, scientists predict more plastic will be in the ocean than fish, including micro-plastics that threaten marine life and contaminate human food and water sources. E-waste and smartphones, largely composed of plastic, are among the fastest-growing waste streams. Food waste is another significant issue, with a third of food produced globally per year—1.3 billion tons—going to waste. The construction sector, reliant on concrete and metals, also contributes heavily to resource extraction and pollution.



In order to observe the management of material resources at their end of life, the author visited the Rhode Island Resource Recovery Center (RIRRC), the primary landfill of the state. The center, situated 250-600 feet above sea level, transformed a dump site into a comprehensive resource recovery facility with eco-depots, small vehicle drop-off areas, composting rows, and wastewater treatment plants.

Recycling is available here for four categories of materials: wood fiber, plastic, metal, and glass. The demand for recycled materials is variable, glass being a current dip in 2022. Other resources, such as methane emissions from the landfill, are captured and converted to fuel to power homes, with excess methane burned as flares. Leachate from the landfill undergoes thorough chemical treatment before being released into the Providence River. Compost rows, known as 'wind rows,' process 20,000 tons of grade A compost annually, which the facility sells at \$8 for 40 lbs. Finally, the site's landscape captures rainwater into swales to protect it against soil erosion.

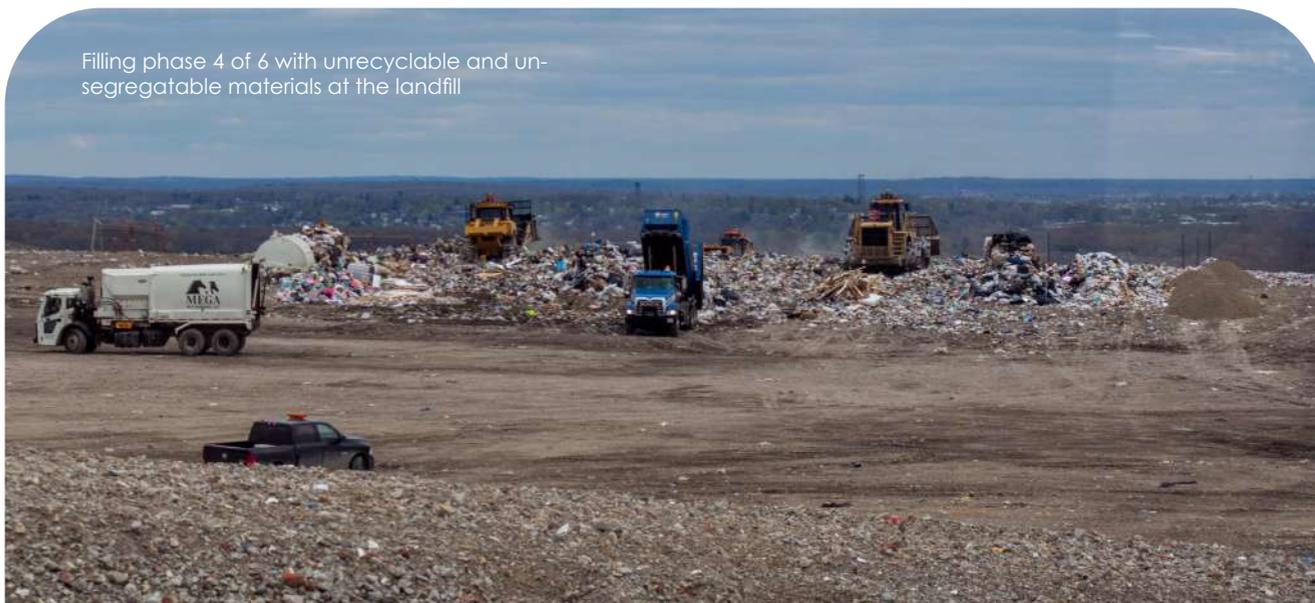
**Despite the extensive facilities at RIRRC, where 380 tons of waste are recycled daily, a notable portion of potentially recyclable materials still end up being discarded as waste.**

Every day, the landfill receives and accumulates tons of trash, consisting of 50% domestic waste, which the team covers with a plastic seal and grass. A significant challenge lies in the fact that many of these materials have the potential to be recycled. The existing facilities face challenges in effectively managing the required quantities. These challenges arise due to limitations in segregation practices and economic constraints that hinder properly handling and recycling these materials. The expansive landfill spans 300 acres, divided into six phases, and experts project the site to cease operations in 2040. Determining recycling content remains manual and cumbersome, with small community recycling presenting a more manageable approach than municipal-level waste management. The challenges of material segregation, manual labor, limited land, and inefficient systems make recycling, even for a small state like Rhode Island, a complex and expensive process.

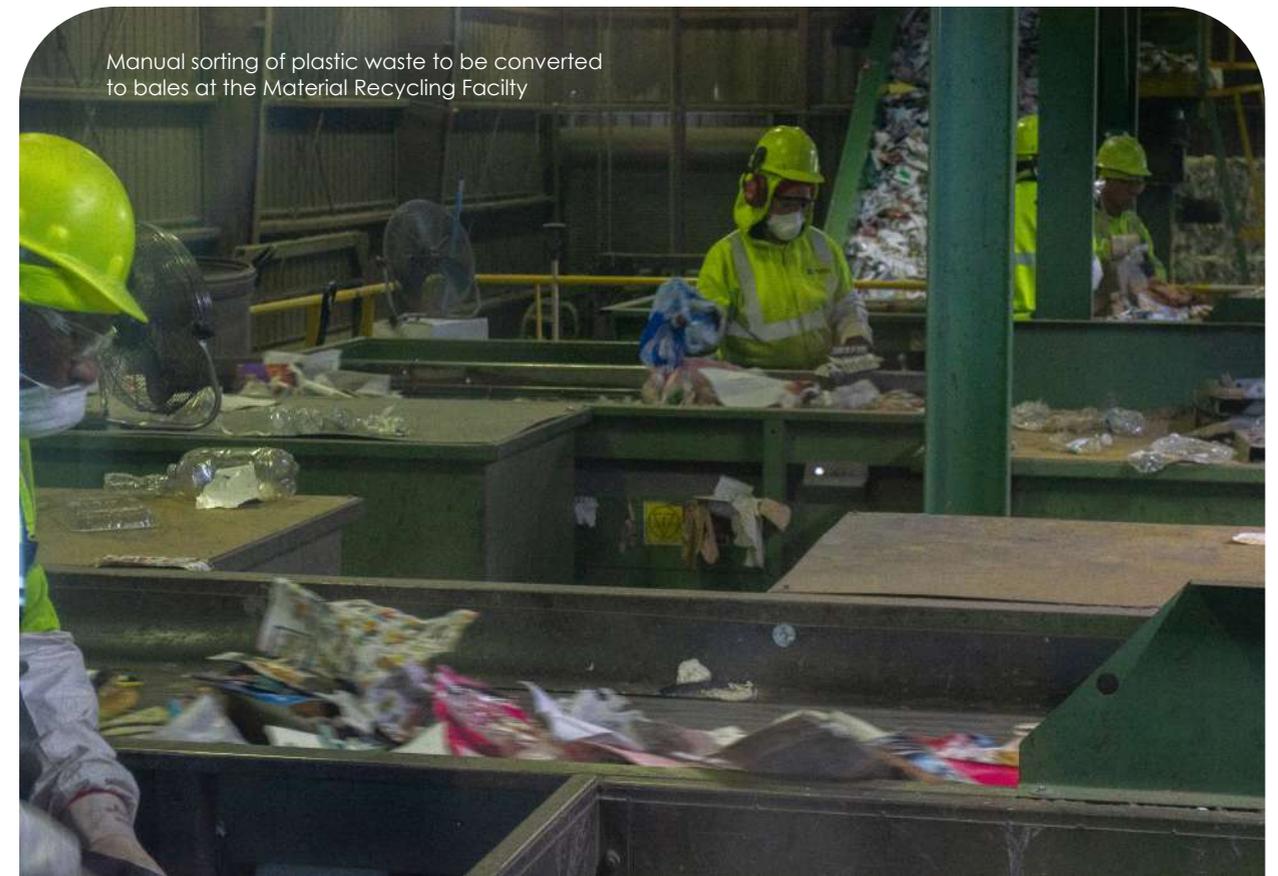
There is a pressing need for innovative solutions that can divert and transform inevitable waste streams while remaining flexible with inputs and providing value to the ecology and the community. Visiting RIRRC provided invaluable insights into recycling and waste recovery nuances and a deeper understanding of the distinct challenges and opportunities inherent in the field.



Filling phase 4 of 6 with unrecyclable and un-segregatable materials at the landfill



Manual sorting of plastic waste to be converted to bales at the Material Recycling Facility





Finding an *Agaricus Arvensis*  
mushroom in Irvine, CA 2019



Mycelium network of thread-like hyphae at 500x magnification

## Nature's Answer to Waste

Nature has long provided elegant solutions to resource management and waste disposal, presenting valuable lessons for addressing the issues of the material domain identified in the previous section. A natural process that could solve our waste problems is that of mycelium, the underground network of fungi. Mycelium plays a critical role in decomposition, breaking down complex organic materials into simpler compounds used by plants and other organisms. It is made of thread-like structures called hyphae, and holds great potential for transforming waste into useful materials.

Researchers estimate that each kilogram of soil contains approximately 200 kilometers of hyphae, which tend to grow more than a few centimeters per day. This characteristic makes mycelium an abundant, widespread, and renewable natural resource (Bonkowski, 2004). The natural process offers a unique opportunity to address waste issues, particularly in organic waste streams and biodegradable materials.

Biological processes also offer valuable insights for waste management through an extensive and diverse network solution. Decomposition, for instance, is a natural process that breaks down organic materials into simpler compounds that other organisms can reuse. By understanding the factors that influence decomposition, such as temperature, moisture, and the presence of decomposer organisms such as fungi, we can improve waste management strategies and develop novel solutions for resource recovery.

The concept of closed-loop systems is one of nature's most powerful examples. In natural ecosystems, materials and resources circulate incessantly through different scales. Waste from one organism becomes food for another, starting and ending with fungi, creating a continuous cycle of consumption and regeneration. By emulating closed-loop systems, we can reduce our dependence on finite resources and aim to bring waste production to zero. This approach goes beyond the foundation of the circular economy, which seeks to keep materials and products in use for as long as possible while extracting the maximum value from them. Moreover, this relates to efficiency. In a parallel sense for our resource, mycelium has also evolved to optimize its energy and material use, ensuring that its functions are not compromised.

As we strive to emulate nature's efficiencies, we must shift our perspective on materials: As Jane Bennet mentions in *Vibrant Matter*, "The figure of an intrinsically inanimate matter may be one of the impediments to the emergence of more ecological and more materially sustainable modes of production and consumption." To incorporate nature's wisdom into our designs, we must view materials as active participants in the process—neither as objects nor subjects, but as interveners or 'operators' catalyzing events. By understanding and leveraging these natural processes, we can create systems that align with the planetary limitations and forces that directly impact us. As we move into the next chapter, we will investigate the fascinating world of mycelium, examining its potential applications and how it can help create a more sustainable future.





PART TWO

# Exploring Mycelium

Deep beneath the earth's surface, a hidden world awaits. As you descend into the realm, the air becomes heavy with moisture, carrying the scent of rich earthiness. Despite the pitch darkness, an enigmatic presence envelops you, sparking curiosity and wonder. A gentle and delicate texture brushes against your foot. You find yourself crouching down, drawn to the mystery unfolding before you. Long strands of pale white weave and sway as if they possess a quest filled with determination. Thousands of interwoven webs form a complex yet beautifully simple structure intricately connected to a larger organic tapestry. Brimming with curiosity, the strange entity explores the subterranean landscape with grace. Upon closer inspection, you realize it is not merely moving but growing! Directing its energy and mass towards newfound sources of sustenance, it breaks down matter and leaves behind a trail of pure elements. As you witness its intricate network, you follow the filaments stretching through a labyrinth, leading you upwards toward the surface. With each push through the topsoil, a rush of oxygen and sunlight greets the once-hidden entity. It transforms into a bulbous yellow mushroom, standing proudly amidst the natural splendor. It becomes clear that this life-form is not a plant, an animal, or a bacterium. With their remarkable abilities, the fungal kingdom reminds us that there is always more to discover if only we venture into the depths.





Invasive phragmites plants growing along the shoreline at Tillinghast Beach.



## Field Research at Narragansett Bay

My curiosity for fungi grew during field research conducted at the eastern shore of Narragansett, near the mouth of the Barrington River in Rhode Island. In this vibrant ecosystem, the Great Blue Heron (*Ardea Herodias*) gracefully waded through the waters while the Piping Plovers' (*Charadrius Melodus*) melodies filled the air. Lush marshes enveloped the area, adorned with native species like Saltmarsh Cordgrass (*Spartina alterniflora*) and the Eastern oyster (*Crassostrea virginica*). Amidst this thriving environment, disruptive species such as the Common Reed (*Phragmites*) also thrive.

During a photography session capturing the site and its wildlife, a fortuitous find emerged—a fallen tree sprouted *Trametes versicolor*, also known as Turkey Tail mushrooms. This encounter sparked a deeper interest in exploring the potential of these organisms to transform waste into new life. Over several weeks, frequent visits to the site allowed for diligent observation and documentation of the growth and development of various fungal species. Insights were sought from local mycologists and ecologists, expanding knowledge about the intricate mutual relationships between fungi, plants, and their environment. The focus was on understanding the unique properties of different fungal species and the ecosystems that supported them.

Observations revealed several species of wood-decay fungi known for their remarkable ability to break down complex organic matter, including lignin and cellulose, emerging as promising candidates for applications in waste management. Further research uncovered the critical role played by fungi in bioremediation, employing living organisms to degrade or remove harmful contaminants from the environment. Certain fungi demonstrated the remarkable capability to extract heavy metals from polluted soils, effectively cleansing the environment and facilitating restoration.

Examining the fascinating world of fungi, the intricate networks of mycelium and the diverse forms of fruiting bodies inspired views of utilizing mycelium as a structural material. In recent years, interest has been resurgent in the sustainable potential of fungi, particularly as an alternative material, incorporating its inherent aesthetic and function into the design of various objects. Primary and secondary research in mycology heightened the understanding of fungi and their ecological significance, opening doors to explore applications of mycelium in industrial design.

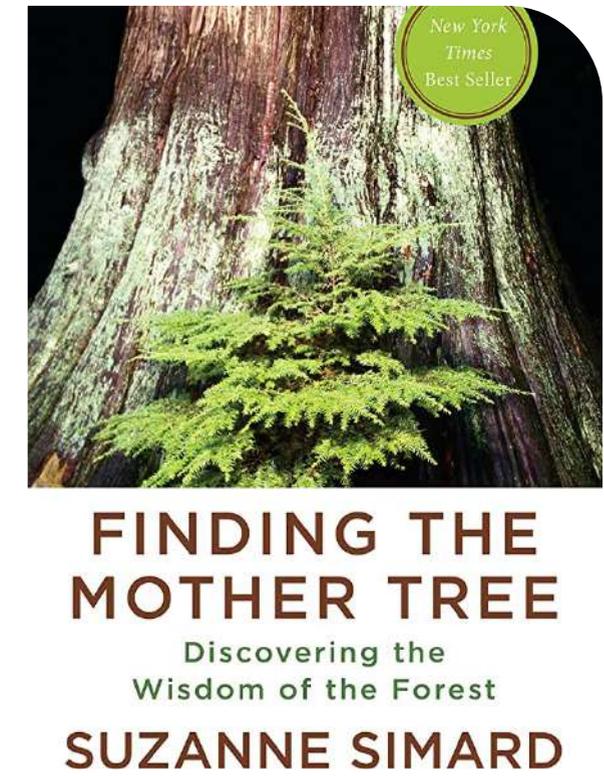
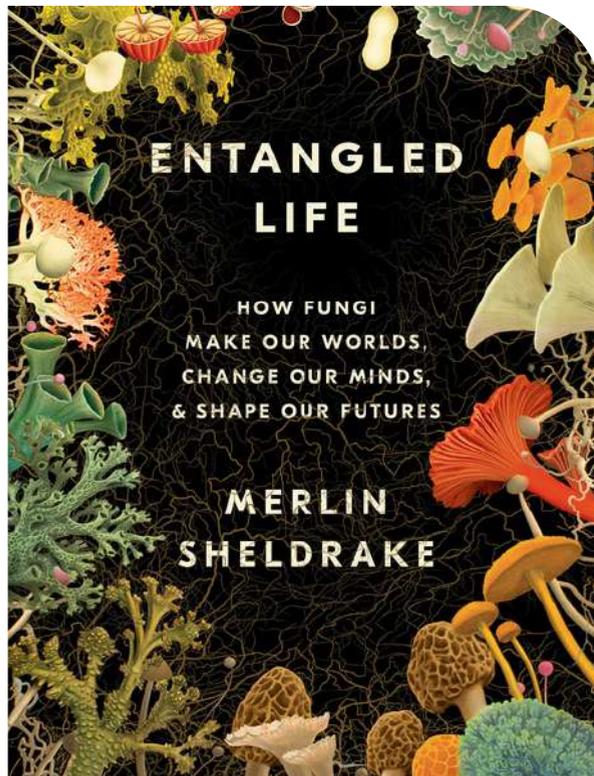
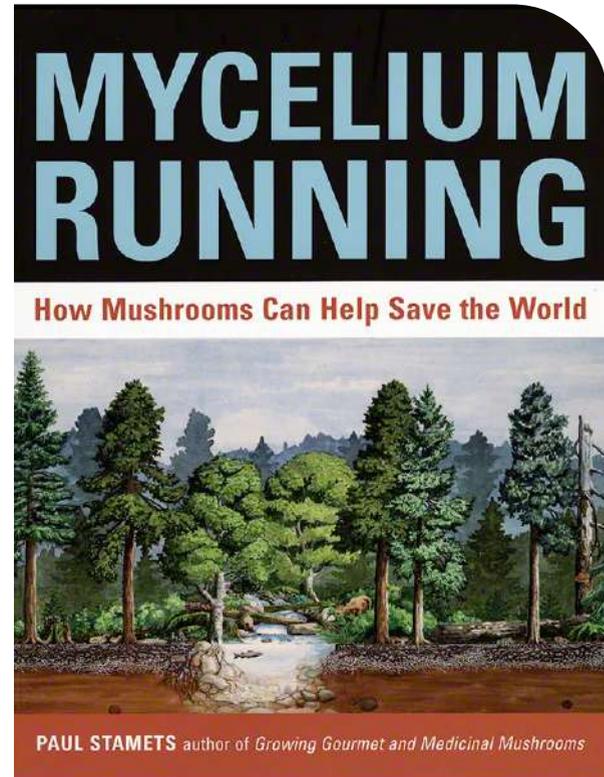
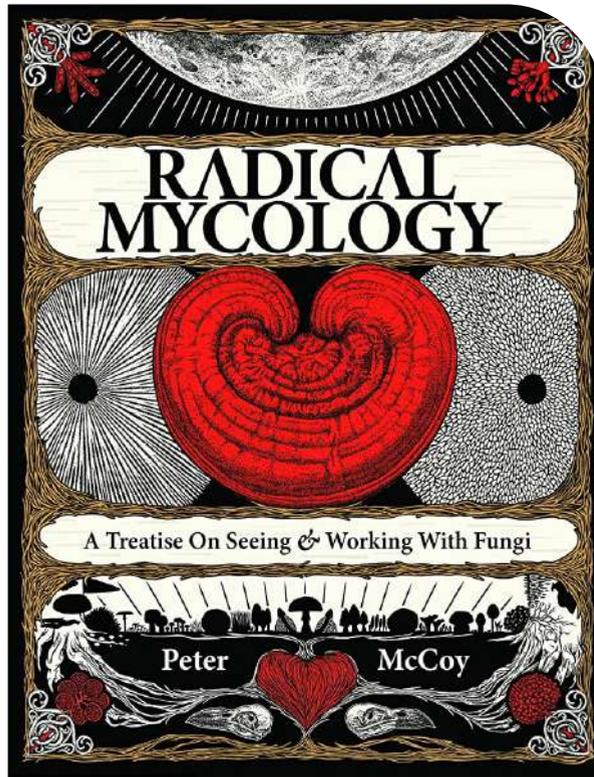


*Microporus xanthopus*



*Trametes versicolor*





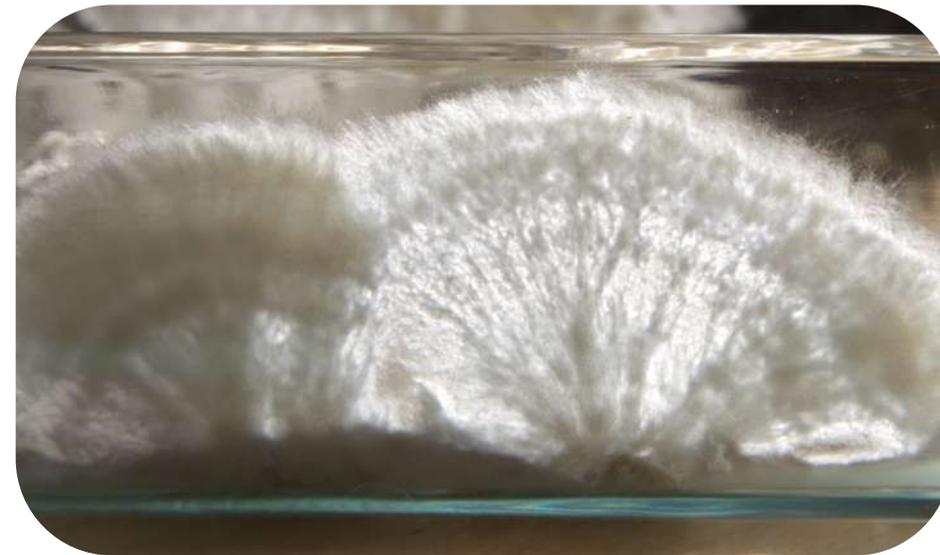
## Literature on Mycology

A diverse set of literary sources spanning across biology, ecology, and potential applications of fungi expanded the horizons of the field for me. Analyzing and extrapolating knowledge from these resources, an inter-disciplinary understanding of mycology shaped the thesis project's development.

"Radical Mycology" emphasizes mycology as a scientific discipline that requires rigorous observation, documentation, and experimentation. The book guides us through detailed protocols, from maintaining logs to ensuring sterile procedures—essential methods for effectively studying and cultivating fungi. It explains how fungi participate in our ecosystems, acting as 'nature's grand chemists.' The crucial understanding of fungal life cycles, growth conditions, and biological properties can lead to new discoveries and sustainable applications.

In "Entangled Life" by Merlin Sheldrake, the author delves into fungal networks' intricate and interconnected nature. He emphasizes the role of fungi as nature's great decomposers and recyclers, breaking down organic matter and making essential nutrients available to other organisms. This concept of fungi as crucial agents of material cycling aligns with the thesis project's goal of re-purposing waste materials into functional objects through mycelial growth. Sheldrake emphasizes the importance of understanding fungi's biochemical flows and processes: "Fungi are masters of transformation, able to break down and build up a dizzying range of organic molecules." By comprehending the complex biochemistry of fungi, it is possible to develop innovative materials and products that exhibit desirable properties and perform specific functions.

Paul Stamets, the author of 'Mycelium Running' explores the potential of fungi to heal the planet by sequestering carbon, remediating contaminated soil, and providing sustainable alternatives to synthetic materials. He states, "Mycelium is the neurological network of nature. Interlacing mosaics of mycelium infuse habitats with information-sharing membranes." This resonates with the thesis project's aim to harness the power of mycelium as a material capable of transforming local waste streams into useful objects. The concept of intelligence, as explored in his work, is crucial to understanding how fungi respond to their environment and adapt to changing conditions. Stamets highlights the importance of this intelligence by stating, them to respond dynamically to environmental stimuli and perform optimally under various conditions. The project aims to explore how this phenomenon of fungal intelligence can be applied in designing materials and products that can dynamically respond to environmental cues.



*Pleurotus Oysterus* mycelium colonizing a glass dish

Throughout history, fungi have played a significant role in traditional medicine practices. For example, mushrooms like *resihi* (*Ganoderma lucidum*) and caterpillar fungus (*Cordyceps sinensis*) were highly valued in ancient China and Japan for their health benefits. In Europe, various fungi species were also used in medicine, such as the tinder fungus (*Fomes fomentarius*) known for its antimicrobial properties. In addition to their health-related applications, fungi have been a staple in human diets for millennia. Edible strains, such as white button mushroom (*Agaricus bisporus*) and oyster mushroom (*Pleurotus ostreatus*), have been cultivated and consumed across cultures. The discovery of the antibiotic properties of the fungus *Penicillium chrysogenum* by Alexander Fleming in 1928 marked a turning point in modern medicine.

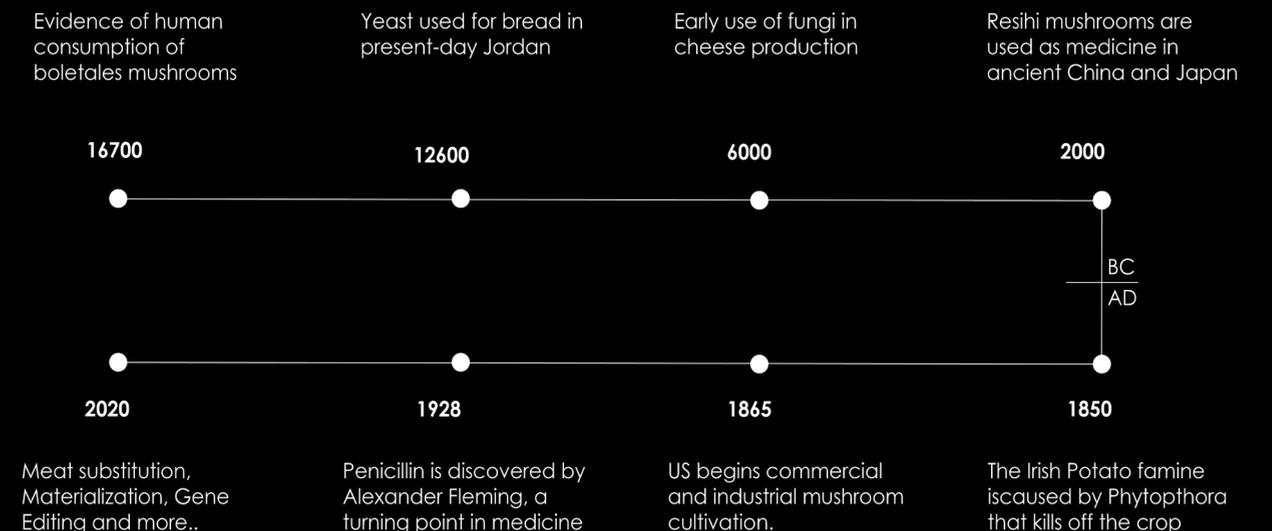
Penicillin revolutionized medical treatment, saving countless lives by effectively combating bacterial infections. Since then, various other fungal compounds have been identified and harnessed for their pharmaceutical potential, such as the immuno-suppressive drug cyclosporine, derived from *Tolypocladium inflatum*. Fungi have also found applications in producing enzymes, organic acids, and other valuable chemicals. For instance, the fermentation *Aspergillus niger* yields citric acid, an essential component in food preservation and flavor enhancement. Additionally, fungi are crucial in producing various fermented foods and beverages, such as bread, beer, and cheese.



Birch fungi of Otzi the Iceman, South Tyrol Museum of Archaeology

The relationship between fungi and humans can be traced back to our early ancestors, the Homo sapiens and Neanderthals. Evidence suggests that early humans utilized fungi for various purposes, from food and medicine to fire-starting. Some of the earliest known examples of fungal use include the discovery of a 5,300-year-old mummy, Ötzi the Iceman, who carried birch polypore fungi (*Fomes fomentarius*) and the red-belt conk (*Piptoporus betulinus*) in his pouch. Birch polypore was likely used for its antiseptic properties, while the red-belt conk was a fire starter.

History of Fungi, extrapolated from Tyler J. Barzee et.al. Future of Fungi Foods, and Scott La Rochelle's Fungi Timeline

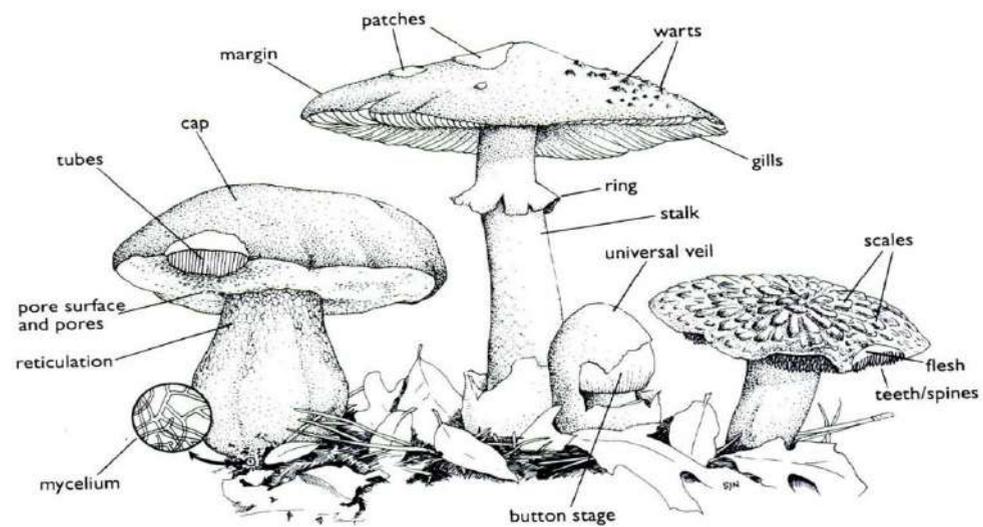


Studying fungi's cellular architecture and composition is crucial for exploring potential applications in biotechnology, medicine, agriculture, and materials. The cell structure and biochemical composition also provide valuable insights into their evolutionary history and relationships. It enables them to thrive in diverse environments, occupy ecological niches, and play essential roles in decomposition and nutrient cycling. Fungi cells primarily comprise hyphae, long, thread-like filaments that comprise mycelium, the vegetative part. The cell walls are made of chitin, a strong and flexible polysaccharide that is also found in the exoskeletons of insects and crustaceans.

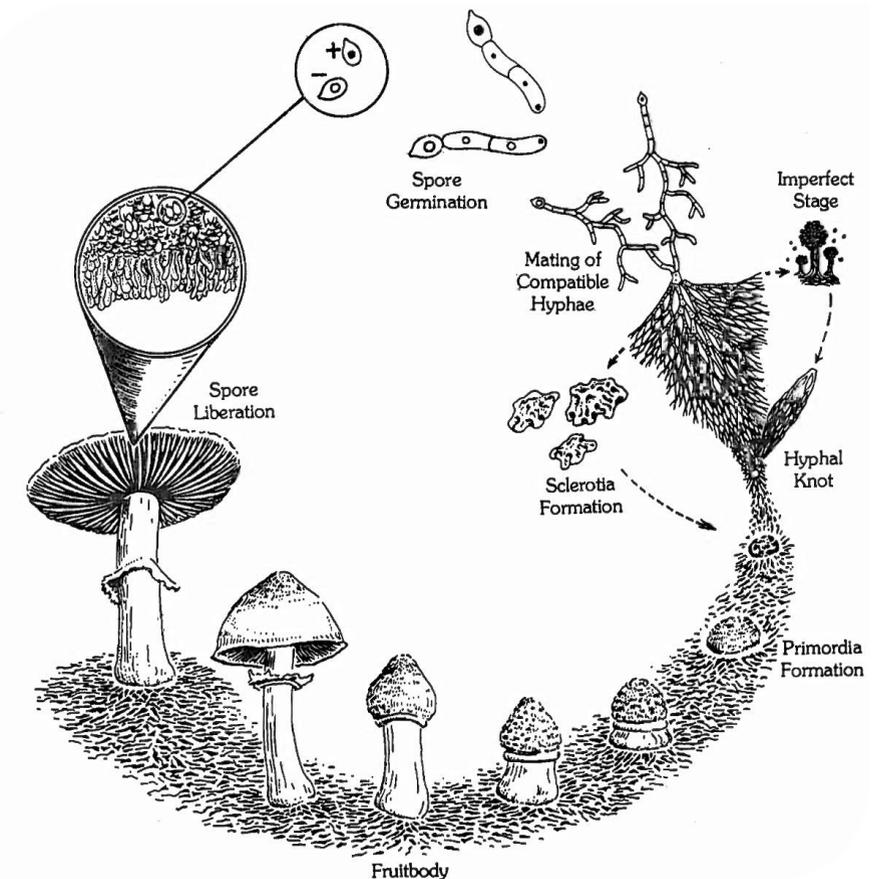
Fungal cells are eukaryotic, containing membrane-bound organelles such as nuclei, mitochondria, and endoplasmic reticulum. The cytoplasm within fungal cells is continuous, meaning that the organelles and cytosol are shared among cells within a hypha through perforated cross-walls called septa. This function allows for rapid communication and nutrient exchange between cells. The cells contain various molecules and compounds contributing to their function and survival. These include proteins, such as enzymes involved in the breakdown and absorption of nutrients, structural proteins like tubulin, and regulatory proteins that control cellular processes.

Fungi also produce diverse secondary metabolites with biological activities, such as antibiotics, mycotoxins, and pigments. These secondary metabolites play a role in fungi's defense, competition, and environmental adaptation. The cells store energy in glycogen, a polysaccharide similar to starch in plants. Additionally, they contain lipids, which serve as energy storage molecules and are important components of cell membranes. Fungal cells also contain various nucleic acids, including DNA and RNA, which carry genetic information and are essential for cellular functions such as replication, transcription, and translation.

Various biochemical processes occur throughout the mushroom life cycle, including producing enzymes for extracellular digestion, cellular respiration for energy generation, and synthesizing secondary metabolites, such as antibiotics and pigments. The life cycle and biochemical processes of mushrooms are vital for their survival and reproduction, and have significant implications for their use in bioremediation, bio-fabrication, and as a source of novel compounds for medical and industrial applications.

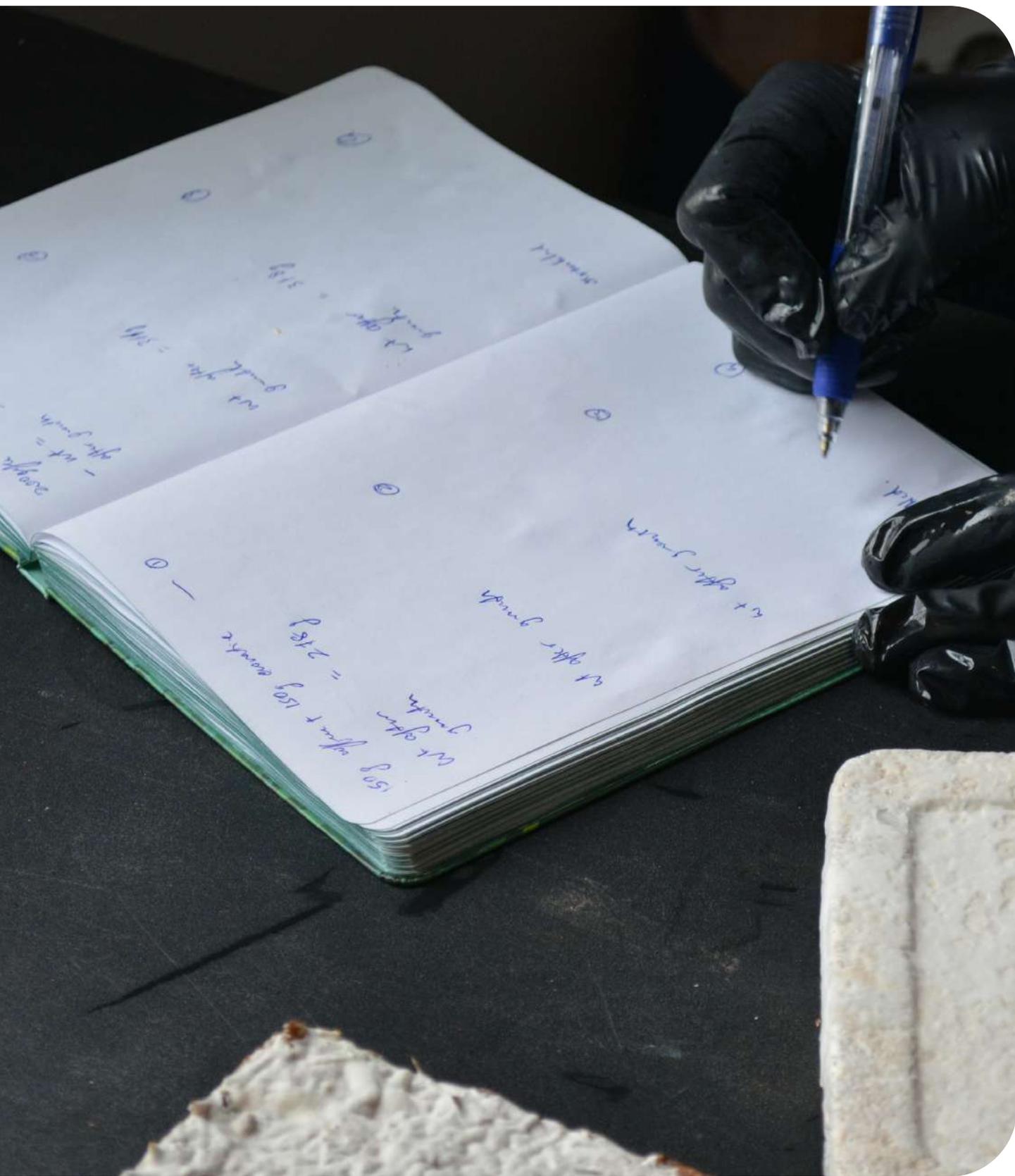


Parts of a Mushroom, Drawing by Sam Noris



Mushroom Life Cycle, Radical Mycology





Logging mycelium experiments and measurements

## Experiments and Design

For most scientists, the preferred research mode is one with fundamental questions, systematic experimentation, and repeatable results. The scientific revolution of discovering underlying patterns found in biology, chemistry, and physics has been instrumental in creating a foundation of knowledge in universal systems. It has completely formed the society we live in today. On the other hand, many designers focus on applying scientific, technological, and cultural data to creative and functional ideas that consider the interconnectedness of people, experiences, and resources for meaningful interventions. Furthermore, in working with biological materials such as mycelium, which have experienced a resurgence in material ecology and industrial design, it is imperative to incorporate scientific and design research methods to adopt an interdisciplinary approach to biomaterial-driven design.

In order to harness the power of fungi and create these materials, a thorough understanding of the process of cultivating mycelium is crucial. This section will explore the best practices for each step in the mycelium bio-fabrication process, which includes workspace preparation, baking, and finishing the final material.

The first step is to mix mycelium with the prepared feedstock during the inoculation process to start growth. This mixture is packed in a petri dish or box, ensuring even distribution to facilitate mycelium binding into a solid structure, which is finally dehydrated, making it safe and functional. Initial experiments to try different mycelium strains, mediums, feeds, and various processes and conditions were an extensive learning process. Maintaining a sterile and controlled workspace for all experiments is critical to cultivating mycelium materials as they are sensitive to contaminants such as bacteria, mold, and other competing microorganisms. Ensuring a clean working environment involves disinfecting the space, tools and equipment using 70% isopropyl alcohol or UV sterilization techniques. Preventing the entry of contaminants into the workspace includes wearing gloves, a face mask, and a lab coat.

Careful selection, transportation, and utilization of ingredients, final products, tools, and spaces are carried out at each growth stage. The objective is to streamline operations, minimize redundant inputs and procedures, and uncover and speculate on the intriguing qualities of mycelium that hold potential for industrial processes and prototypes.



## EXPERIMENT I

# Mycelium Strain and Medium

Practicing cultivation of various species of fungi allowed for the observation of their entire lifecycle, from mycelium colonization to fruiting body emergence. Understanding the organism's lifecycle and the time required for growth was crucial for optimizing the bio-fabrication process. The time taken for the coffee grounds experiment with liquid culture highlights the need to explore new recipes and techniques to accelerate bio-fabrication. One potential avenue for faster growth is the investigation of different fungal strains and their specific growth characteristics, as suggested by the book *Radical Mycology*.

Consulting with other designers exploring mycelium revealed that the Turkey Tail strain exhibits relatively faster primordia formation. Another possibility is incorporating additives such as wheat bran and rice flour into the substrate, providing conducive nutrients for growth. Different species of fungi exhibit various properties and characteristics, making it important to select a suitable strain for the intended application. The strains I used include *Ganoderma lucidum* (Reishi), *Pleurotus ostreatus* (Oyster), and *Hericium erinaceus* (Lions Mane) due to their availability. Native strains are more likely to be adapted to local conditions, reducing the need for extensive environmental control and resource consumption during growth.

Strain	Species	Medium	Time	Notes
S1	<i>Ganoderma Lucidum</i>	GIY (Ecovative)	30 days	Colonization and primordia formation had growth outside of the mold box
S2	<i>Ganoderma Lucidum</i>	GIY (Ecovative)	38 days	Fruiting body formation was achieved with higher humidity during the last week
S3	<i>Ganoderma Lucidum</i>	GIY (Ecovative)	NA	Primordia formation started as small mushrooms but ultimately stopped due to low moisture
S4	<i>Hericium erinaceus</i>	Grow Kit	39 days	Fruiting body formation was extensive and grew two large mushrooms
S5	<i>Pleurotus ostreatus</i>	Liquid Culture	NA	Fruiting body development was slower and stopped due to low moisture

Time for fruiting body growth



## EXPERIMENT II

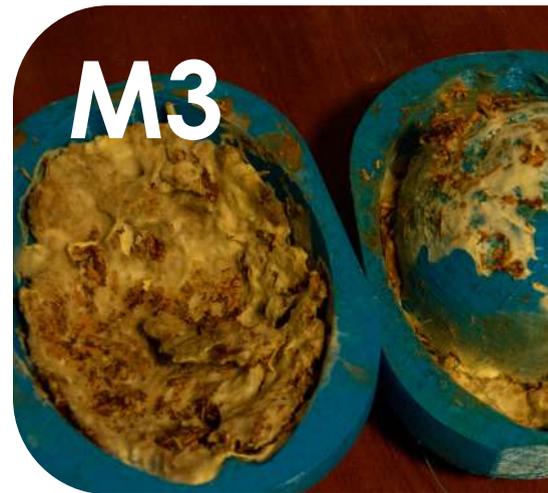
# Feedstock and Growth

In this experiment, we test different substrates for their ability to support mycelium growth, with sawdust and coffee grounds yielding the best results. Previous research has shown that these materials are rich in nutrients that support fungal growth, such as lignin, cellulose, and nitrogen (Stamets, 2005; "Mycelium Running"). By using local waste streams like sawdust from maker spaces and coffee grounds from cafes, with the inputs being flexible, affordable, and available, this experiment aligns with the thesis's goals of resilience and resource access. The successful growth of mycelium in these waste materials demonstrates the potential for a locally-based approach to material production and waste conversion. For the possible contamination issues due to the uncontrolled nature of waste materials, we also need to investigate pre-treatment processes to standardize the quality of waste materials.

Mycelium can grow on various organic substances, including wood, paper, and agricultural waste. The raw material must first be broken down into smaller pieces or particles to provide a suitable substrate for mycelium growth through shredding, chipping, or grinding. Next, it is essential to sterilize it to eliminate any potential contaminants, which can be done using heat (autoclaving, pressure cooking, or baking) or chemical methods (soaking in bleach or hydrogen peroxide). After sterilization, the substrate should be drained and cooled to room temperature. Further steps include studying the variability in nutrient content, pH levels, and material properties for potential applications between different sources of sawdust, cardboard, and coffee grounds.

Feed	Biomass	Source	Sterilization	Time	Notes
F1	Used Coffee Grounds	Collected from local cafes (Nitro Bar, PVD)	Microwave	12 days	With pre-existing moisture and partial sterility, it optimized resources
F2	Saw Dust Waste	Collected from local makerspaces (The Wurks, PVD)	Boiling Water	12 days	As a wood by-product, this feed grew quickly and consistently
F3	Cardboard Scrap	From Amazon packaging boxes	Isopropyl Alcohol	15 days	This worked as a feed, but was slower and needed shredding

Time for mycelium creation



### EXPERIMENT III

## Mold Design and Process

Molds are vital for shaping and containing the mycelium material throughout growth. Previous experiments using Petri dishes and standard plastic boxes focused on optimizing growth factors rather than exploring material properties, fabrication techniques, and potential product outcomes. From an industrial perspective, researchers have identified the ideal geometries that allow mycelium to interact effectively with the mold, ensuring structural integrity during and after growth. Depending on the desired application and design constraints, these molds can be crafted or fabricated using various methods and materials, including cardboard, vacuum forming, or 3D printing.

Multiple factors come into play when selecting a suitable mold material and design. Considerations such as the desired final shape, ease of mold removal, and potential for mold reuse play significant roles in the decision-making process. Additionally, ensuring the mold's cleanliness and sterility before usage is critical to maintaining a conducive environment for mycelium growth. During the inoculation process, makers carefully mix the mycelium medium with the prepared feedstock, creating a well-blended mixture packed into the designed mold. This step aims to ensure an even distribution of the mycelium medium within the mold, providing adequate space for proper mycelium growth and effective binding of the material.

Mold	Process	Material	Design	Time	Notes
M1	Vacuum Forming	PET	formed on objects	15 days	These molds were a success but were limited to simple geometries and added wastage.
M2	3D Printed	PLA	2 part mold with alignment slot	15 days	TPU was 3D printed at 10% infill which caused cracks to appear and didn't allow full growth.
M3	3D Printed	TPU (flexible)	2 part mold	15 days	3D printing PLA allowed customization and complex geometries, and added a line texture to surfaces.
M4	Craft	Cardboard	cutting and taping	15 days	Material dried out due to the porous nature of cardboard. Humid environment or mold lining is required to hold moisture in the substrate.

Time for mycelium creation



G1



G2



G3



G4

**EXPERIMENT IV**

**Geometry Design**

This study explored the impact of geometry and shape on the structural integrity of mycelium materials. The experiment's findings revealed that geometries with thicker surfaces without sharp edges demonstrated greater relative structural stability. This holds significant value for creators who aim to develop mycelium-based products that can withstand loads while maintaining their intended functionality. One can create purposeful, efficient products by comprehending the interplay between geometry, material properties, and mycelium growth.

Cultivating myco-materials that balance structure and sustainability presents a unique challenge. Designers must navigate the complex interplay of these factors to develop lightweight forms and structurally sound products. The future scope includes developing computational design tools that optimize geometry based on desired material properties and use-case requirements. By leveraging the power of these tools, we can explore a broader range of forms and identify other patterns or correlations between geometry and integrity, opening up new possibilities for innovation.

	Shape	Design	Notes
G1	Cube	3D printed with one face open	A gap between the substrate and film allowed a surface layer of mycelium to form, improving surface quality.
G2	Sheet	3D printed with one face open	Higher surface area of this mold led to evaporation, low growth and crumbling of material.
G3	Sphere	3D printed in two hemispheres	A fully enclosed and dark mold for a sphere also led to low growth and crumbling. The curved surfaces held better integrity than previous sharp corners.
G4	Tetrahedron	3D printed with one face open	This shape had moderate structural integrity. Corners were crumbling.



**EXPERIMENTS V and VI**

**Dehydration and Compression**

The fully colonized mycelium material undergoes baking to halt mycelium growth and eliminate any remaining living organisms. Typically, this step involves placing the material in an oven or dehydrator, setting the temperature to 200-220°F (93-104°C), and allowing it to bake for 8 to 12 hours. The challenge lies in mitigating warping, especially for flat sheets that tend to bend upwards from the edges due to uneven heating. Three solutions were tested and validated to address warping: applying weights to the material, opting for lower temperatures for extended periods, and flipping the materials by 180 degrees every 30 minutes.

As an alternative to traditional baking, the exploration delved into using a hydraulic press as the final step in the process. This innovative approach aimed to streamline the process, optimize resource utilization, and enhance material performance by increasing density through compression. Implementing this method not only addresses the issue of warping, but it also significantly reduces the dehydration and hardening time to just 1 hour, compared to the 12 hours required in the oven. This advancement offers a more efficient and time-effective solution for achieving the desired material properties.



	Feed	Feed Weight	Mycelium	Pre-Weight	Post-Weight
O1	Coffee Grounds	200g	200g	400g	208g
O2	Coffee Grounds	200g	200g	400g	207g
O3	Coffee Grounds	200g	200g	400g	210g
O4	Coffee Grounds	200g	200g	400g	212g
O5	Saw Dust	150g	150g	300g	130g
O6	Saw Dust	150g	150g	300g	138g
O7	Saw Dust	200g	200g	400g	169g
O8	Saw Dust	300g	300g	614g	236g

	Method	Feed	Sample Size	Plate Temp.	Dimensional Change (z)
C1	Heated Compression	Coffee Grounds	4" x 4" x 1"	200g	-77%
C2	Heated Compression	Saw Dust	4" x 4" x 1"	200g	-70%
C3	Post-baking Compression	Coffee Grounds	4" x 4" x 1"	200g	-62%
C4	Post-baking Compression	Saw Dust	4" x 4" x 1"	200g	-58%

## Qualities of Myco-Materials



**Surface layers** of mycelium are maximized to 3 mm thick, improving structural integrity and surface texture



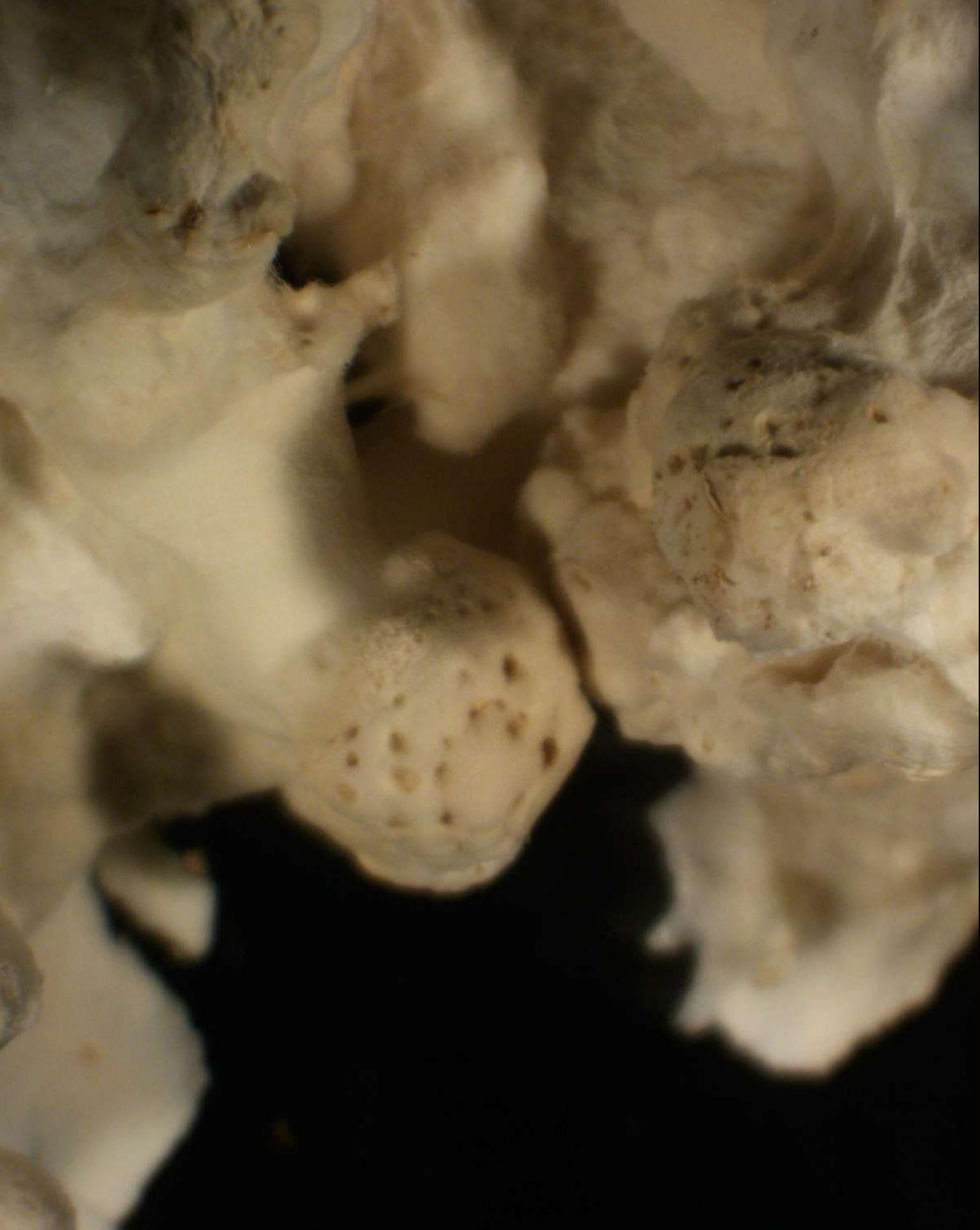
Mycelium has the ability to **self repair, heal and fix** disconnected areas and broken parts through its natural growth and binding process.



In separate experiments it was found that the selected mycelium strains **avoid contaminants** such as the trichoderma fungus.



It can be further **coated and finished** through sanding, sealing, or applying wax, oils, or paints to enhance the material's aesthetics and durability.



## Biofabrication Methods

Mycelium, as a material, possesses inherent qualities that set it apart from conventional materials. Its behavior, reactions, and transformative properties demand a distinct mindset and approach to cultivation that requires meticulous care.

Current methods of mycelium growth encompass a range of techniques, including mono-tubs, grow-tents, and additive manufacturing such as 3D bio-printing. Each method offers unique advantages and considerations. Mono-tubs and grow tents provide compact or scalable solutions for mycelium cultivation in controlled environments. These methods typically involve creating a space where the mycelium substrate and growth medium can thrive.

The advantage of these setups lies in their flexibility and adaptability to different project scales, from small-scale experimentation to larger production runs. Cultivators can create optimal conditions for mycelium growth and maximize the yield of high-quality materials by controlling temperature, humidity, and light exposure.

On the other hand, 3D bio-printing offers advanced capabilities for precise material deposition and complex geometric structures. These technologies enable the fabrication of intricate designs with intricate internal structures, opening up possibilities for customized products with tailored material properties. However, such methods often require specialized equipment and expertise, making them more suitable for research institutions and innovation settings.

PROCESS I

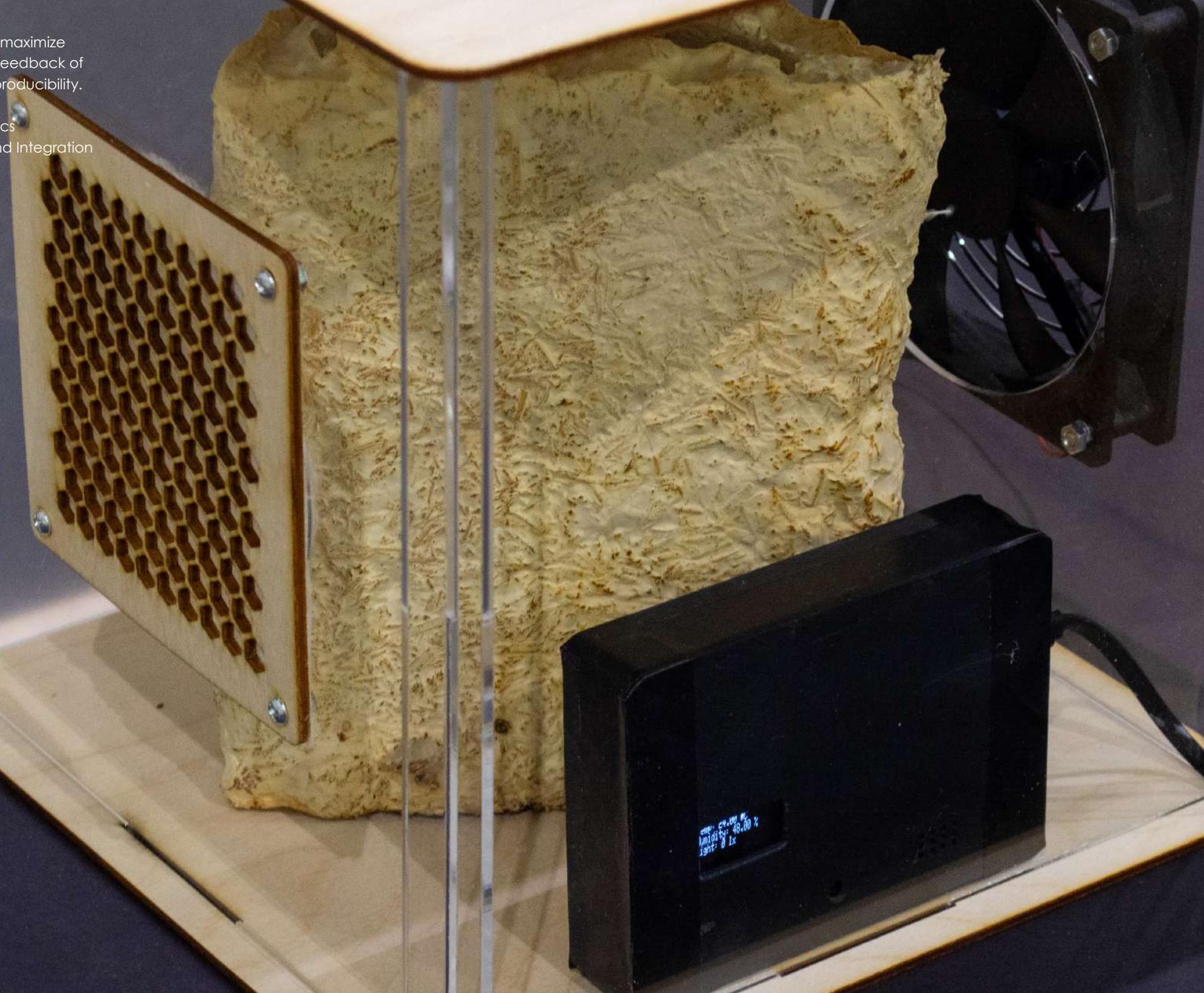
# Myco-Tub

Myco-tub is a concept for airflow to maximize mycelium growth, with sensing and feedback of conditions for measurement and reproducibility.

Materials: Acrylic, Plywood, Electronics

Process: Laser Cutting, 3D Printing and Integration

Dimensions: 12" x 12" x 12"





An early prototype in monotub development

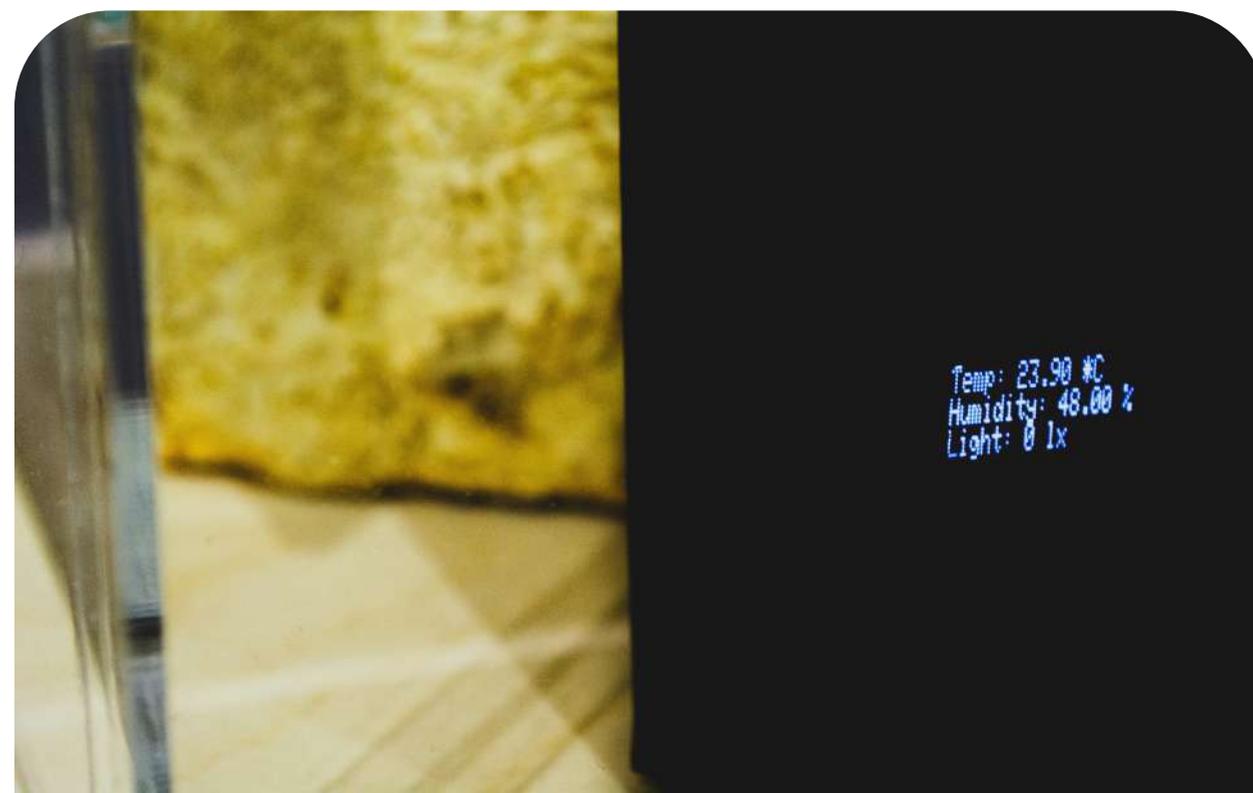
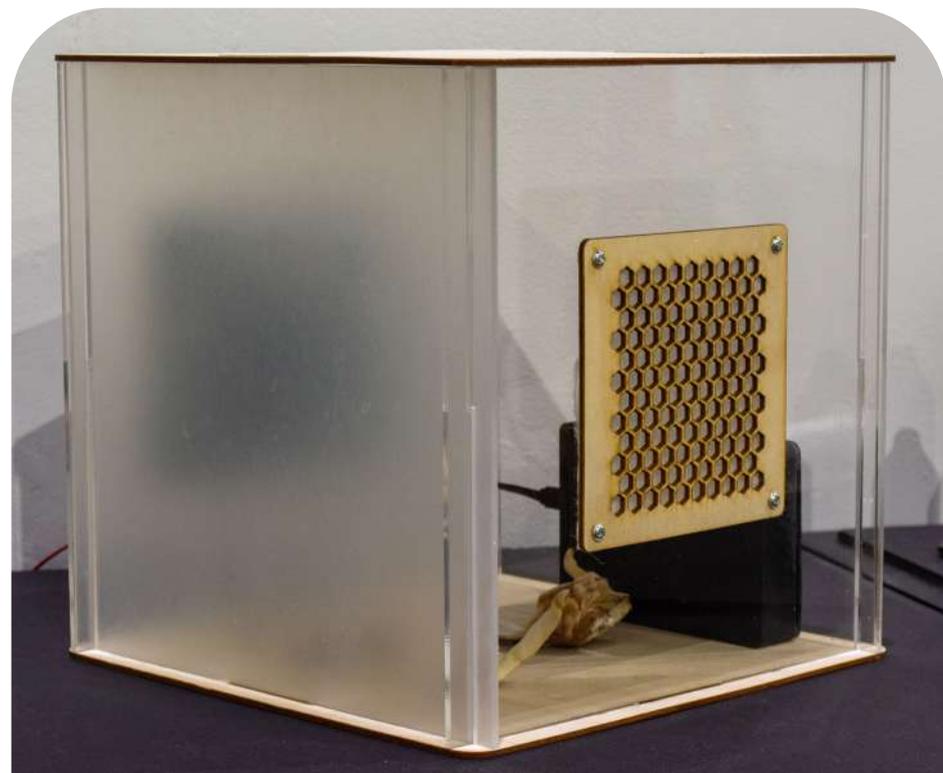


Modified plastic containers as Low-fidelity monotubs

Grow tubs, or mono-tubs, serve as a common method for cultivating mycelium and harvesting mushrooms. These portable and cost-effective structures are widely used, particularly for small-scale cultivation. However, they come with limitations such as restricted air exchange, inadequate humidity control, and limited capacity.

To address these challenges and optimize the grow tub design for experimentation and design purposes, a custom monotub concept was explored. The aim was to enhance interaction, sensing, and feedback capabilities. Cardboard prototypes and mockups were utilized to investigate potential improvements in these areas.

The Myco-Tub incorporates laser-cut acrylic sheets for the enclosure, an industrial fan with a true-HEPA filter and metal grill, as well as a 3D printed case housing sensors for temperature, humidity, and light. Real-time data from these sensors is displayed on an LED screen, enabling precise monitoring and adjustment of growth conditions. With enhanced airflow and adjustable settings, the myco-tub provides an improved environment and versatile platform for mycelium molds and experiments. It enables greater control over critical parameters like air exchange, humidity, and light, facilitating optimal conditions for successful biofabrication experiments and design exploration.



PROCESS II

# Myco-Tent

Myco-Tent is a medium sized chamber with humidity and ventilation control for improved production and testing capacity of molds and materials.

Materials: Steel, PVC, Humidifier, Air Exchanger

Process: Assembly and Integration

Dimensions: 4' x 2' x 4'



70g sawdust  
140g coconut  
Tile 9  
Mar 12

200g coffee  
200g cardo  
Mar 12

TILE 9  
sawdust: 100g  
myco : 200g  
water : 30ml  
Mar 10

200g coffee  
200g eco  
10g water  
TILE 8  
Mar 12

3/8  
problems  
fermate  
- 10g, 20ml  
- 10g, 1ml, 2ml

TILE 3, 4, 5  
100g eco + 20g myco  
200g eco + 200g myco  
Mar 11

200g coffee  
200g cardo  
TILE 6  
12 Mar

UNMEASURED  
apple wood snicker  
- eco

200g coffee  
200g eco  
30g water  
TILE 7  
Mar 12

After conducting experiments with a customized grow tent setup at home, the focus shifted to establishing a dedicated mycelium station at RISD Coworks Lab. This station was equipped with a benchtop sterilized workspace, a grow tent, an air exchanger and automatic humidifier, a hydraulic heat press, and other tools required for bio-fabrication. This setup focused on bio-fabricating consistent materials by controlling the conditions and optimizing the process. By maintaining fixed environmental conditions and refining the fabrication methods, it was possible to produce mycelium sheets with uniform properties, a key factor to the development of reliable products.

To promote optimal mycelium growth, providing the appropriate environmental conditions is essential. These include maintaining a relative humidity of 80-90%, a temperature of 70-75°F (21-24°C), adequate air exchange, and partial or filtered light. To maintain these conditions, the inoculated mold should be placed in a humidity-controlled, partially enclosed chamber. Monitoring and adjusting the environment to ensure healthy mycelium growth is important. The lessons learned from this experiment can be applied to other forms of mycelium bio-fabrication, contributing to developing a more robust and adaptable process.



Mycelium workspace assembled at home with a 3D printer for custom molds.



Semi-automated grow tent assembled at CoWorks Lab as a medium-large sized workspace.

PROCESS III

# 3D Myco-Printing

A syringe pump attachment that can be integrated with traditional fused deposition modeling (FDM) printers to extrude mycelium composites.

Materials: Carbon-fibre PLA, Stainless Steel, Electronics

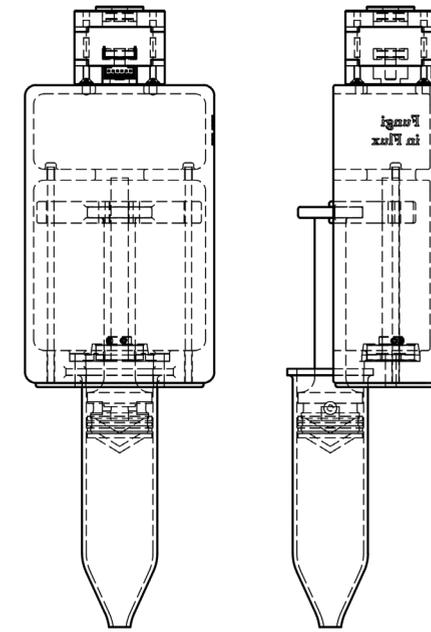
Process: Mechanical Engineering, 3D Printing

Syringe Volume: 150 ml



The final exploration in bio-fabrication of mycelium is 3D myco-printing, an experimental procedure that involves blending a homogenous mycelium mixture and extruding it through a motorized syringe. The experiments used two open-source 3D printers: Creality Ender 3 V2 and Kennedy Liu's K3Delta, to connect our syringe attachment for mycelium. The first few iterations were a series of syringe prototypes for diameter size and a formulated blend of local coffee grounds, mycelium, and water to extrude the paste. The enclosure and plunger mechanism were developed next for the syringe attachment system.

Throughout the trials, several challenges emerged, including concerns about contamination risks and the struggle to achieve structural integrity beyond a height of 30mm. However, with further refinement of 3D myco-printing, the potential to create intricate and complex organic structures using mycelium-based materials becomes more promising. This technological advancement presents exciting opportunities for rapid and customized prototyping of biomaterial objects, pushing the boundaries of design and additive bio-fabrication.

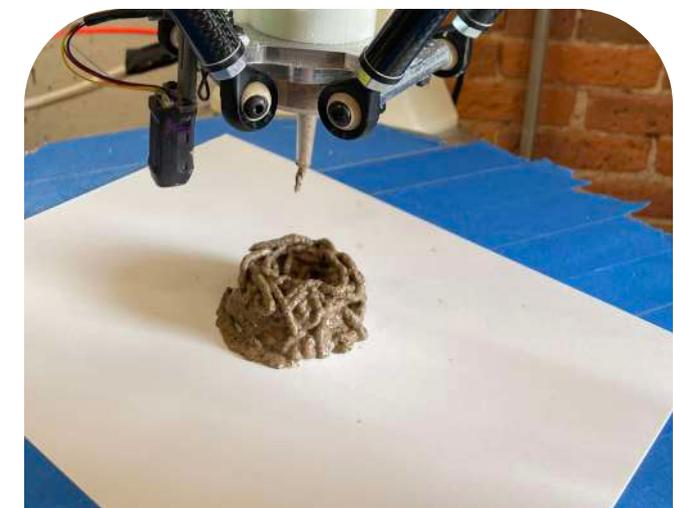


CAD drawing of mechanism

Automated mycelium extrusion



Manual extrusion experiments tested various compositions and paths for flow and adhesion of consecutive layers





# Material Characterization

Material Characterization is a critical component in exploring and developing mycelium-based materials. This part of the research aims to study the fascinating, multifaceted process of characterizing mycelium, not just from an industrial standpoint but also from an experiential one. The complex interplay of these diverse perspectives holds the key to unlocking the full potential of mycelium as a tangible and valuable alternative to traditional materials.

The study starts with mechanical testing and measurements of density, strength, water absorption as fundamental indicators of a material's physical properties. In parallel, it is equally crucial to appreciate its experiential aspects, as these attributes often profoundly impact how the material is perceived, interacted with, and ultimately integrated into our lives.

Graduate students from different departments at the Rhode Island School of Design came together in an organized workshop to capture the essence of experiential characterization. Their diverse backgrounds and expertise provided a rich tapestry of perspectives, enabling us to explore and understand the sensory, interpretive, and affective responses evoked by myco-materials.

This approach toward mycelium material characterization sets the stage for a comprehensive study of the material's capabilities and potential applications. It highlights the importance of integrating both quantitative (scientific) and qualitative (experiential) analysis to create materials that fulfill criteria and resonate with us.

## ATTRIBUTES I

# Mechanical and Physical

Mechanical testing evaluates mycelium materials' specifications for safety and resistance to failure in various contexts, ensuring the final product meets the required performance criteria. By understanding these, designers and engineers can determine the suitability of mycelium materials for applications in consumer goods, construction, packaging, textiles, or others.

Three key mechanical properties selected for characterizing mycelium;

**Compressive strength:** The ability of the material to resist compression forces, such as those experienced in structural and loading applications.

**Water Absorption:** The capacity of the material to resist collecting moisture influences its durability and suitability for various indoor and outdoor environments.

**Density:** The suitability of the material in reducing the product weight, contributing to its effects of strength and material resource and energy consumption for ecological impact.



Myco-block sample compressed till failure in UTM at Brown Design Workshop.

### 1. Compressive Strength

An Instron Universal Testing Machine (UTM) at the Brown Design Workshop was used to test seven samples: five Myco-blocks and two Myco-sheets. The samples had a cross-sectional area of 20 mm x 20 mm. Results showed that the Myco-blocks had an average compressive strength of 0.17 Mpa. On the other hand, the Myco-sheets exhibited a significantly higher compressive strength at 0.46 MPa (2.7x). It is worth noting that the Myco-sheet samples were made by partially joining four sheets, and actual values may be much higher than shown.

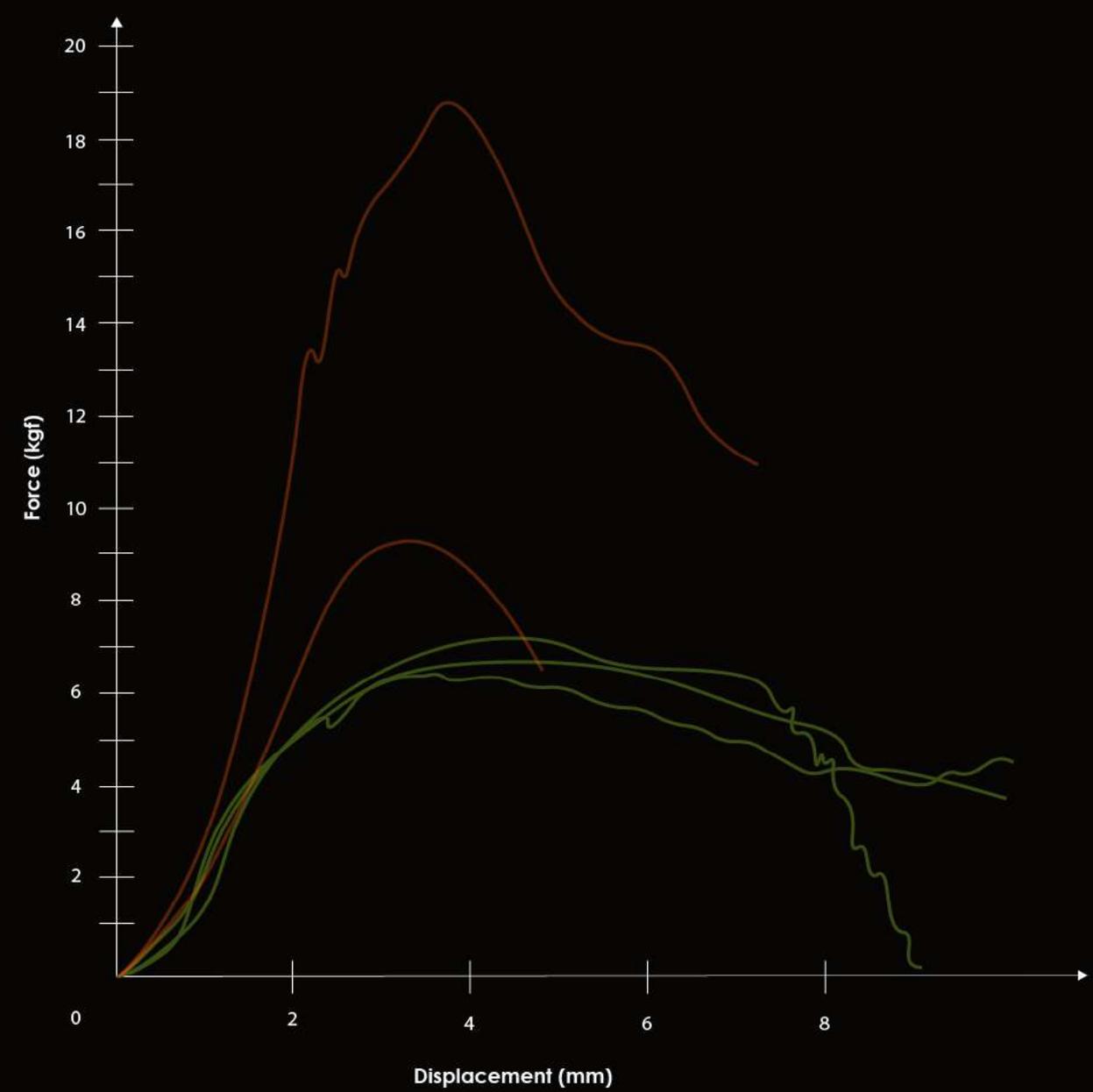
When comparing these values to other commonly used materials such as Styrofoam, wood, and foam-core, mycelium demonstrates superior compressive strength compared to Styrofoam and foam-core. However, it falls slightly below most types of wood, suggesting that mycelium-based materials can be suitable for applications that require moderate structural support and durability. In particular, they can be a viable alternative to traditional materials such as packaging, insulation, and lightweight structural components.

### 2. Water Absorption

The water absorption properties of myco-materials, 130-190% over 24 hours indicate their propensity to absorb and retain water. This characteristic suggests potential applications where water management and control are crucial, such as agriculture and landscaping.

- Myco-block
- Myco-sheet

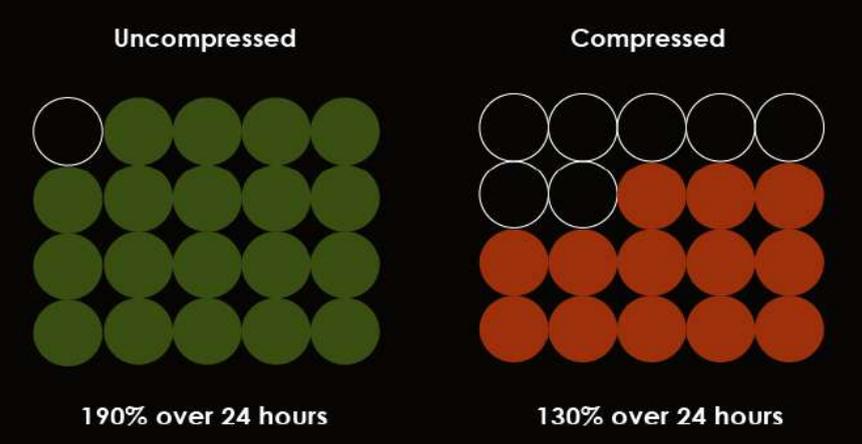
### Stress-Strain



### Density



### Water Absorption



## ATTRIBUTES II

# Experiential and Sensory

In this section, we analyze a study by Camera, Serena, and Elvin Karana 'Experiential Characterization of Materials: Toward a Toolkit' and develop a survey for characterizing mycelium materials, with a focus on performative, affective, interpretive, and sensory aspects. From a design perspective, the experiential scope will help better understand perception, behaviours, emotions and usability of the material. After initial testing, a workshop at RISD Grad Exchange in April 2023 was organized to share this project and gain valuable insights through feedback from students.

Survey cards compared two versions of mycelium samples: uncompressed (myco-sheets) and compressed (myco-sheets). The 15-20 minute activity drew participation from 40 graduate students representing various departments and providing diverse perspectives. The participants' responses indicated a significant interest among students in further exploring the materials. 62% of the participants expressed their interest for material testing and prototyping and requested samples of custom composites. This enthusiastic response is a testament to the growing demand and fascination surrounding mycelium within the design field.



40 responses collected during a workshop presentation at 20 Washington Auditorium

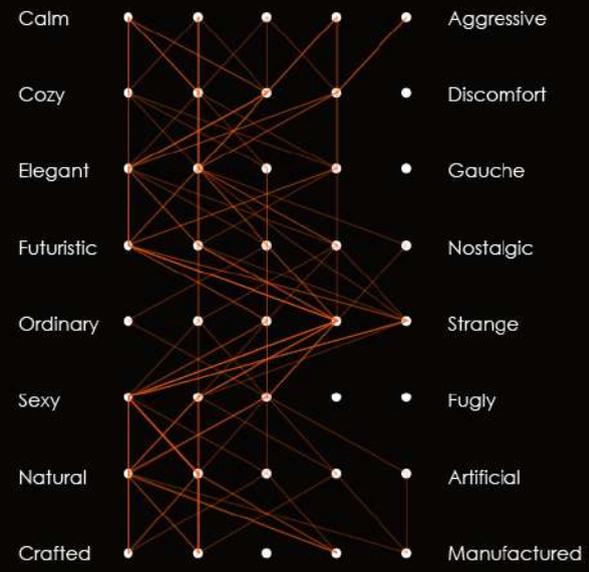
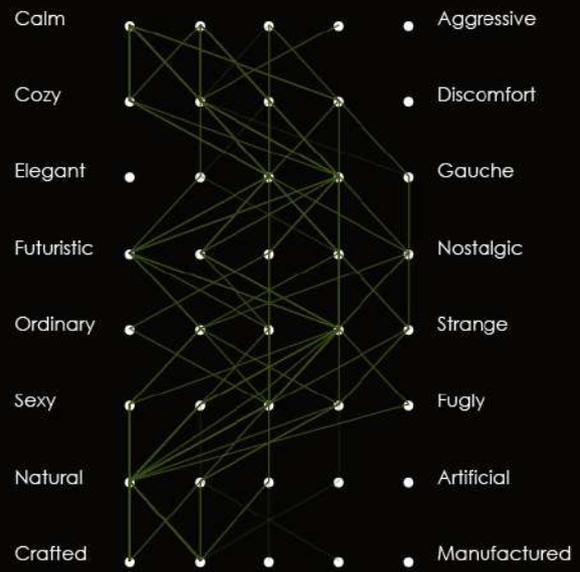


Experiential attribute toolkit and survey for comparing Myco-blocks and Myco-sheets.

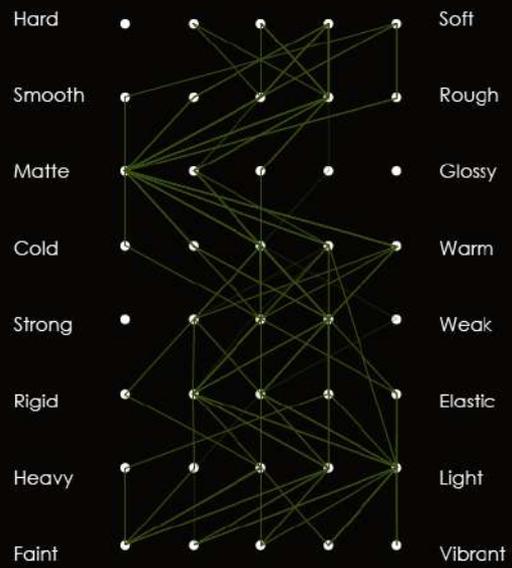


## Interpretive Attributes

● Myco-block  
● Myco-sheet



## Sensory Attributes



## Affective Attributes



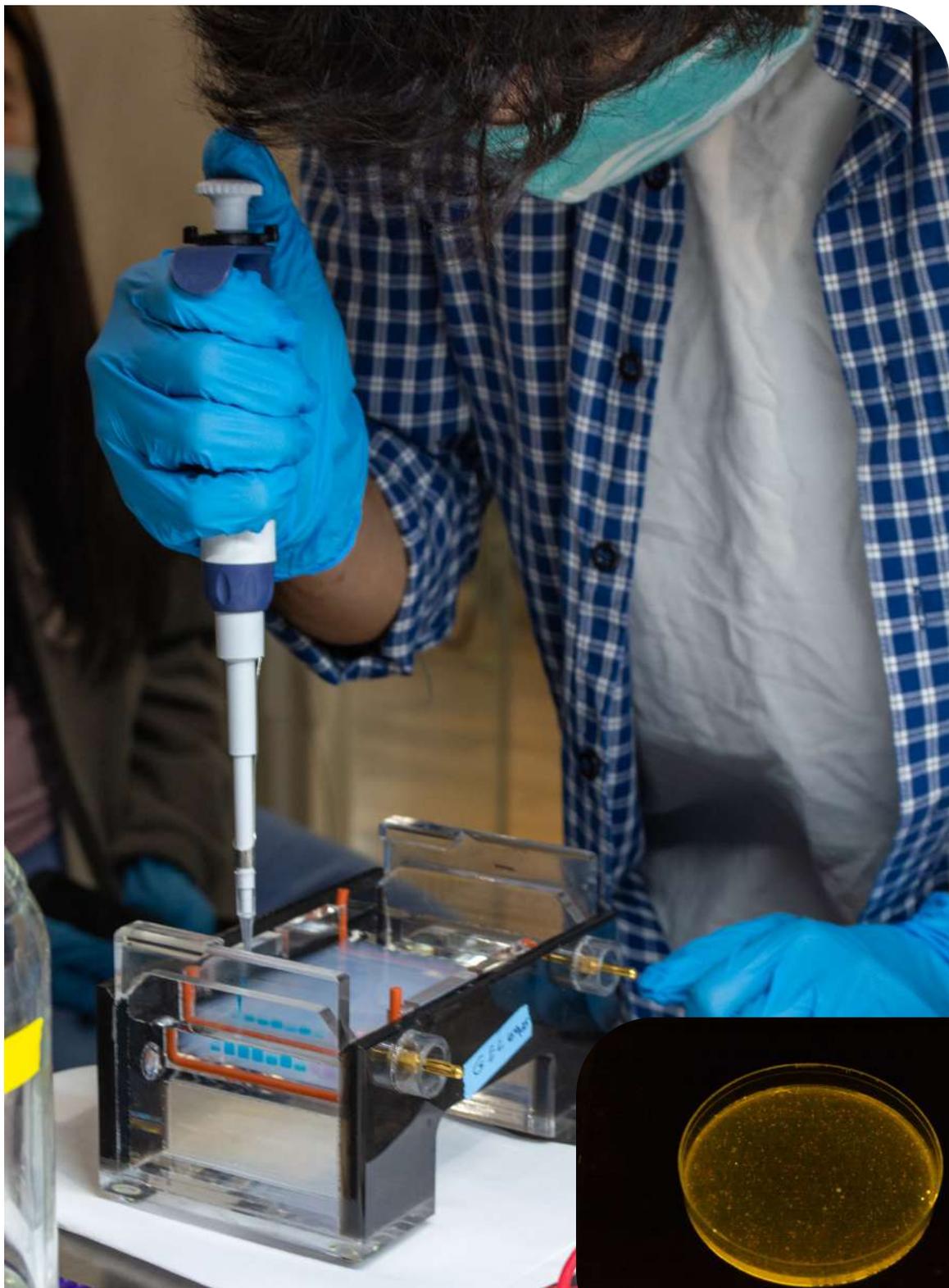




An early myco-product exploration with Shravan Rao to make lightweight, breathable and biodegradable fracture casts.

PART THREE

# Cultivating Products



Performing a CRISPR Cas-9 protocol on yeast cells at GenSpace Lab



## Precedents in Bio-design

In the winter of 2023, I was fortunate to be the teaching assistant at the RISD Global course, Biodesign NYC. Here our cohort marvelled at various innovations in biomaterials, biomimicry, and biophilia. We visited companies and laboratories across Brooklyn and Manhattan, where we had the privilege of hearing from founders, scientists, designers, and researchers. These encounters provided us with deep insights into a biology-driven model's industrial and cultural aspects.

During a talk by Suzzane Lee, the founder of Biofabricate, we observed samples of mycelium materials utilized by companies like Mogu to construct tiles and insulation panels, exhibiting multi-layered mycelium foam composites. In a conversation with Grace Knight, designer at Ecovative, we gained insights into the controlled environment used for growing mycelium in large chambers. We discussed techniques such as ventilation to enhance the thickness capacity of mycelium materials. One of the things that came out of our class discussion with Grace, was the amount of contamination and waste they have tried to minimize in their industrial process. It's a challenge that should be acknowledged in this thesis and is not to be underestimated.

In another meeting with Andrew Dent, the Chief Materials Scientist at Material Connexion, we gained insights into the potential timelines of biomaterials as compared to plastics, emphasizing the importance of responsibly sourcing carbon and leveraging its role in the life cycle of the material. We got to see and touch numerous remarkable material samples from a database of thousands, broadening our knowledge. Finally, he underscores the fact that a biomaterial that seems better for the planet may sometimes in fact be worse, due to how it's used and its fate.

One of the most exciting experiences was performing a CRISPR experiment to manipulate the DNA of yeast for color alteration at GenSpace Labs. We visited the BioBAT Art Space, witnessing the collaborative efforts between scientists and artists in creating artifacts and exhibits that push the boundaries of biology. At the Art Lab in the SVA, we studied more precedents and tools for biomaterials used in various sculptures and structures.

All of these talks with Elena Soterakis at BIOBAT, Mitch Joachim at TerreformOne, Andrea Lipps and Caitlin Condell at Cooper Hewitt Museum, Aaron Nesser at AlgiKnit, Ross McBee and Uyen Tran at TomTex, Rachel Rosenkrantz at Atelier Rosenkrantz, and Dan Grushkin at Biodesign Challenge; opened up a multitude of possibilities for biodesign, leaving a lasting impact on our understanding of the field.



Tarah Rhoda, Bio Art Lab, School of Visual Arts



Andrea Lipps, Cooper Hewitt Museum



Aradhita Ajaykumar Parasrampurua, Genspace Labs



Suzanne Lee, Biofabricate



Andrew Dent, Material Connexion



Ken Lewis, SOM



Mycelium materials and objects at Bio Art Lab, School of Visual Arts



Bacterial phosphorescence at Bio Art Lab, School of Visual Arts



Slime Mold (Myxomycota) at BIOBArt Art Space

Mycelium samples demonstrated their versatility of material qualities through novel growth techniques. The slime mold navigation exhibit exemplified nature's phenomenal intelligence and problem-solving capabilities, offering insights into decentralized systems. Bacterial phosphorescence showcased the interplay of biology and light, revealing the potential for bioluminescence. Biomaterial experiments explored various biological compounds and fabrication methods. Beyond biodesign concepts, the artifacts at various labs, studios, startups, and other spaces in NYC disseminated the connections between materials, technology and ecology.



Biomaterial experiments at GenSpace Labs



### Composter Kit, DailyDump

Solving for waste management, gardening and convenience, the form and interaction connect to the sentimentality of indigenous and native craft.



### NotPLA

What if we ate our packaging instead of discarding it? Daily interactions and behaviors can change from a new mode of responsible consumption.



### Ecovative

Pioneering myco-technology and a myriad of products for food, textile, packaging and creative applications.



### Earthship

After watching 'Don't Flush your Freedom' to build towards the idea of self-sufficiency with what's available, moving towards a life of adequacy.



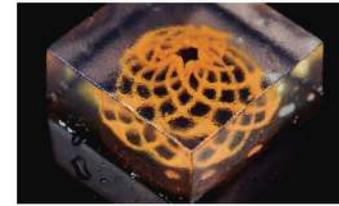
### Carbon3D

Using a lattice design software and novel 3D printing, tuned and high performance products are generated for custom, decentralized supply chains.



### Biomason

Sporosarcina Pasteurii binds sand with urea to produce bricks using bacterial induced precipitation and producing a by-product Ammonium.



### Fluidic Edibles, Morphing Matter

The gel scaffolding embedded material bath preserves shapes during printing and the toolpath design allows free-form multi-dimensional printing.



### Bio CellX, Cellink

Bio-dispensing cell culture with bio-inks, a new modality of discovery, control and reproducibility is created for tissue and disease modeling.



### Biohab, Bits & Atoms MIT

Invasive disruptions such as the Namibian encroacher bush can be adapted to local models for food security and dignified housing using mycelium.



### NoMy, Snohotta

Industrial symbiosis with submerged fermentation of mycelium sound panels in a nutrient rich waste stream.



### Atelier Luma

Unconventional agro-industrial residues: rice straw, sunflower residues are rapidly proliferated by the myco-structure to make insulation panels.



### ForestWool

From pine needles to fiber, this maximizes the use of already existing biomass to diversify the largely mono-culture driven textile industry.



### Man-Nahata, Oxman

Self-organizing an urban-landscape into a nature-centric biosphere, new social structures can be morphed from the built to grown megalithic elements.



### Vyoh, Frog Design

Using moss to filter air, Vyoh is housed in the interior environment. Sustaining its life with bio-inputs might be the key to prolonging the product impact.



### Well Proven Chair

A chemical reaction mixing timber and bio-resin, expands into a strong foamy material. This exuberant property surrounds the leg structure.



### DungSe

From cattle waste to building material, DungSe's approach considers even the cow as a stakeholder, where healthier food gives consistent outputs.



### Kelsun, Keellabs

A novel drop-in technology backing biopolymers, actors in the fashion industry can adopt this technology, to improve scalability and viability.



### Sway

Julia Marsh talks about the idea of biological circularity, paired with performance, composting and new experiences to revolutionize packaging.



### Mylo, BoltThreads

Targeting luxury fashion with myco-textiles, engineered in vertical farms, significant bio-based content is added to fabrics for biodegradability.



### Hot Wire Extensions

Using waste nylon powder from SLS printing, an electrified nichrome wire melts and grows the contacted sand-nylon mixture in flexible sizes.



### Microbial Home, Phillips

As utilities that our lifestyles demand are wasteful and disconnected, biological machines could provide gas, water, lighting and HVAC.



### SeaTech, Loliware

The algae pellet is compatible with injection molding machines and designed to disappear, radicalizing bio-material manufacturing.



### Precious Plastics

Semi-industrial machines that shred, extrude, mold and sheet-press plastic waste, opening a whole world of possibilities to creators.



### Ribera, Krill Design

Rekrill's patented process intercepts orange, lemon peels, coffee grounds from the food chain and turns them into a on-demand 3D printed product.



Model shop, RISD Industrial Design Department

## An Alternate Approach to Prototyping

The increasing demand for sustainable materials in educational institutions, particularly in design departments such as architecture, interior architecture, and industrial design, necessitates a shift away from reliance on materials like foam and plastics. In the ID shop on the fourth floor, the generation of substantial foam waste during prototyping is a prevalent issue, resulting in its disposal at the end of the semester or even earlier. Addressing this challenge requires exploring and adopting alternative materials that align with sustainable practices, minimizing waste, and promoting a more environmentally conscious approach to design education.

Interviews with students and faculty at the Rhode Island School of Design revealed that the same experience concerning harmful materials and their waste resonated across departments. On-campus student organizations such as the Green Campus Initiative, Brown RISD Innovation Community, and Regenerative Earth Collective have biomaterial innovation as one of their primary focuses in events.

RISD's Nature Lab and CoWorks Lab are the primary hubs for exploring and learning about biomaterials. However, the successful fabrication of biomaterials, especially delicate organic materials like mycelium, requires the maintenance of specialized equipment, optimal conditions and streamlined processes. Currently, the labs face significant challenges due to the overwhelming student demand, affecting their ability to provide the necessary resources and support.

In Fall 2022, discussions at the RISD Center for Complexity, Nature Lab, and the Division of Architecture and Design students voiced the need for suitable materials incorporated with scientific rigor and regenerative strategies in their educational curriculum. Over the past few years, students across departments have significantly needed sustainable materials. Therefore, a combination of practicing and teaching about biomaterials and fabrication is an important first step toward achieving positive environmental impacts. From an institutional standpoint, there needs to be an effective solution that fits within the infrastructure, to improve access to biomaterials and engage students.

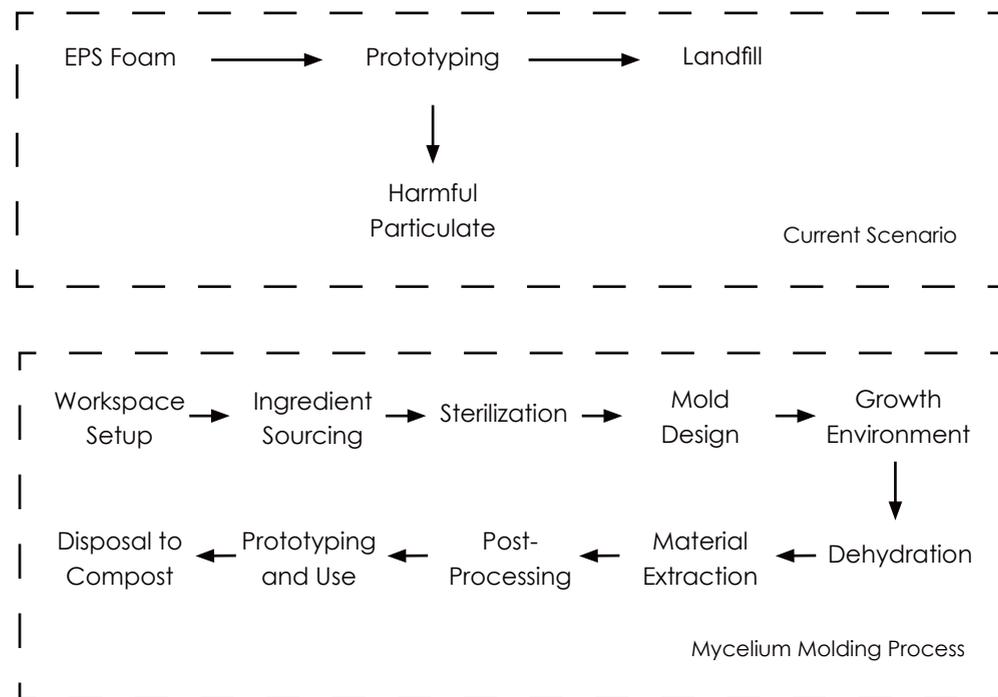
## WORKSHOP I Mycelium Molding

Replacing foam with mycelium-based composites at RISD required addressing challenges in traditional mycelium molding processes. By understanding pain points, substrate selection, mold design, preparation, and growth conditions were specifically improved to establish a new material system that overcomes limitations. In Winter 2023, the author co-taught a 2-hour workshop in collaboration with Calgary Haines-Trautman during the course Mold(ing), where student participants from various departments at RISD cultivated objects using custom vacuum-formed molds.

To address material concerns at RISD, an alternative approach is designed to mitigate the cumbersome, expensive, and wasteful process of growing mycelium materials from scratch. The workshop provided valuable insights into the key considerations for setting up mycelium molds for students. Manufacturing mycelium-based raw materials offer a promising substitute for petroleum-based foams, providing effective, biodegradable, standardized forms that enhance student access to sustainable prototyping materials.



Participants packing molds with mycelium-waste mixture



Comparison of EPS use and mycelium molding process



Workshop explorations grown and processed after 2 weeks

MATERIAL I

# Myco-Block

The pre-fabricated mycelium blocks reduce the need to grow materials while offering artists, designers, and makers a sustainable and non-toxic material for using with manual and machine tools in prototyping.

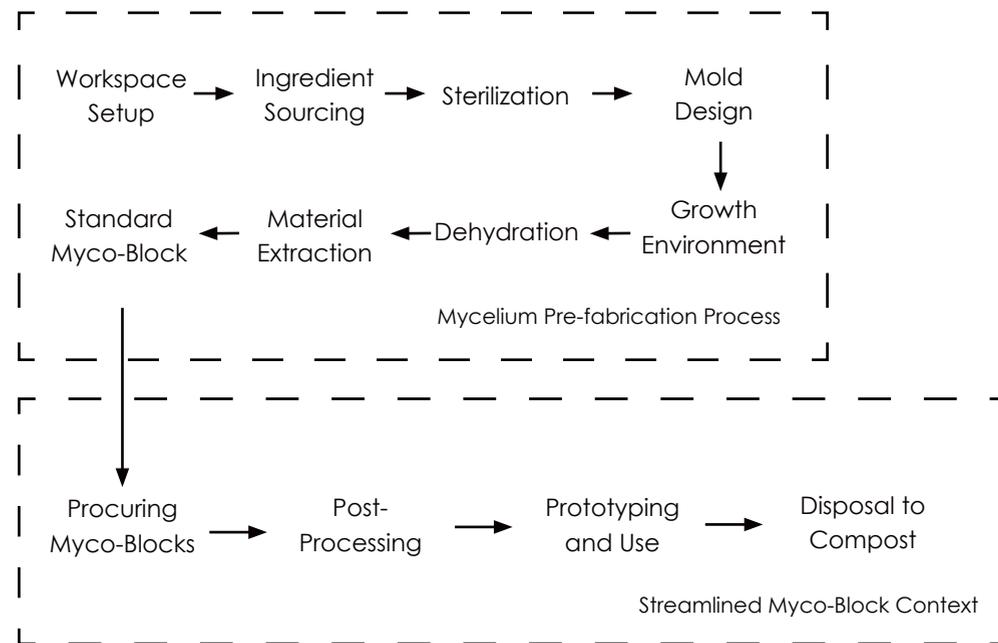


WORKSHOP II

# Myco-Block Prototyping

The next workshop at the RISD Center for Integrative Technologies convened a diverse group of enthusiastic graduate students to engage hands-on with mycelium, a versatile material they had heard about but had yet to interact with. The workshop introduced pre-grown materials that offered flexibility, creativity, and sustainability in prototyping as an alternative to growing mycelium from scratch.

The workshop began by setting the space with a range of myco-block sizes and shapes, a series of manual tools and access to power tools and shop machines. The workshop was designed to be open-ended and observational, to provide each participant with an opportunity to creatively experiment, experience the material and observe its behavior under various processes, treatments and design interventions.



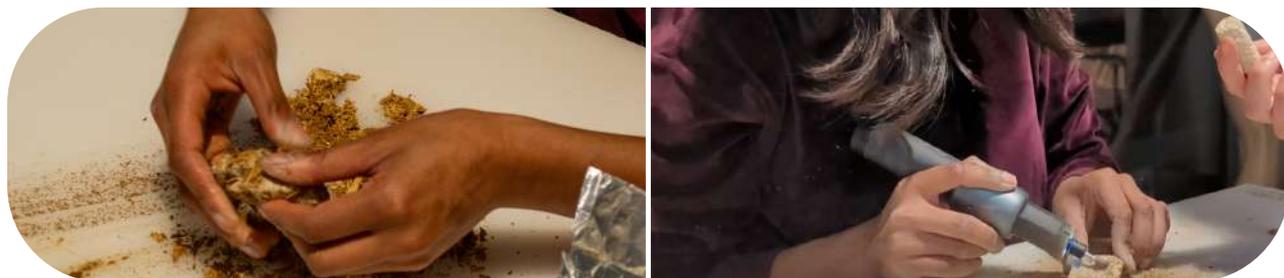
Pre-fabricated myco-brick system



Workshop participants selecting pre-fabricated mycelium materials and tools for making with



Workshop outputs and creations



Process images of five design workflows using myco-blocks.

The workshop nudged participants to explore the creative potential of mycelium-based composites. Through hands-on making, they cut, shaped, and joined the material, testing the boundaries of its possibilities. This collaborative atmosphere encouraged learning, experimentation, innovation and exchange.

The first process focused on creating an architectural model by cutting and gluing myco-bricks. They cleverly combined the bricks with balsa sticks and wool threads. The mycelium bricks were easy to cut and shape, providing an ideal low-fidelity prototyping material for conceptualizing organic landscape models.

An artistic approach was taken by a second process experimenting with a material collage. The mycelium bricks became their canvas, onto which they added components of acrylic paint, paper, wood, clay, and even metal. Although mycelium did not provide a substantial grip for screws, the material was easy to manipulate, and its porosity interacted with mixed media.

The third process explored the textures and finishes. They carefully sculpted a pre-molded mycelium object with a Dremel, finishing it with two layers of spray paint. A rough, organic texture emerged that contrasted with the synthetic sheen of the paint, in an aesthetic juxtaposition.

Another artifact integrated a molded mycelium object with wood and springs, exploring the material's potential in motion-based applications. They were pleasantly surprised by the lightweight nature of the mycelium and its ability to hold inserted components securely. It encouraged them to investigate further the sound and kinetic effects of mycelium.

Lastly, a student embraced the idea of form sculpting, shredding the mycelium, and mixing it with clay. The malleability of the mixture presented a new scope of sculptural possibilities, allowing the creation of structures with varying rigidity depending on the mycelium-clay proportions.

Overall, the workshop proved that pre-grown mycelium materials could offer an alternate approach to growing mycelium from scratch, which can be time-consuming and challenging for prototyping. The benefit of myco-blocks is their versatility to conform and break down, their low-fidelity nature that enables creativity and sustainability, and their inherent qualities of waste transformation and biological circularity. Despite the limitations, such as in sanding, handling screws and inserts, and certain processes like laser cutting being inappropriate due to the material's charring nature, with denser and more rigid mycelium materials as the next step, compressed composites or 'myco-sheets' could hold promise to address some of these concerns.

MATERIAL II

# Myco-Sheet

The heat-compressed mycelium sheets at a thickness of 1 to 2 mm are dense and rigid, suitable for laser cutting, machine tools and high-performance applications.





Laser cutting and raster engraving on myco-sheet samples at CoWorks Lab





Nitro Bar Cafe, Providence

## Temporary Biodegradable Objects

According to a study by the National Coffee Association, Americans consume around 400 million cups daily, producing approximately 140 million pounds of coffee grounds weekly generating 3 million tons of waste annually. A significant amount of this ends up in landfills, producing large amounts of methane, a potent greenhouse gas that accelerates global warming.

Interviews with various stakeholders at cafes in Providence, with owners, employees, and customers, helped gather perspectives and activities regarding climate friendly practices such as Fairtrade-certified sourcing and local composting. Learning that it is a cost to have the waste picked up for compost, organic by-products generated by the cafes could also be converted into products they can produce locally and sell to customers as an additional revenue stream. We needed a site segregating coffee ground waste in a separate container in a scheduled fashion, which our system can pick up.

Nitro Bar sources their coffee beans equitably and maintains a separate container for waste grounds which conveniently addresses sterility. The waste gets scheduled for a mid-day and end-day pick up, covered in nearby lab and looped back as products. By using waste from Nitro Bar itself and making products for the cafe, it not only reduces the burden on landfills but also significantly cuts down transport and processing energy for producing interior objects, adhering to the principles of the circular economy.

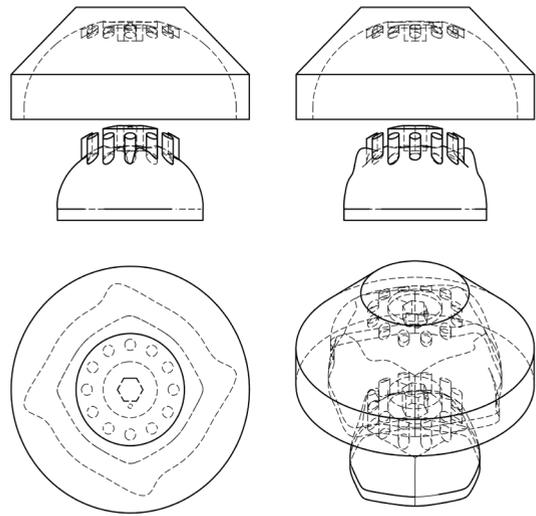
After an initial exploration into coffee coasters made from mycelium, the next development was to create value products such as smart mycelium lamps, integrating electronics and mycelium planters, focusing on biodegradability. These products described next are larger in mass to capture carbon, relatively complex in form and function, and have a higher frequency of use and lifetime, contributing to their ecological impact.

CONCEPT I

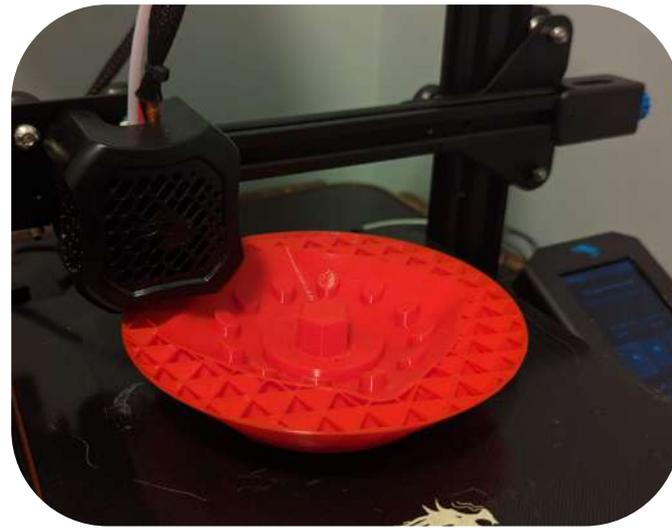
# Myco-Lamp

The smart mycelium lamp is an ambient lighting product that detects motion to emit a biophilic blue glow through the mycelium shade.





CAD drawing of mold



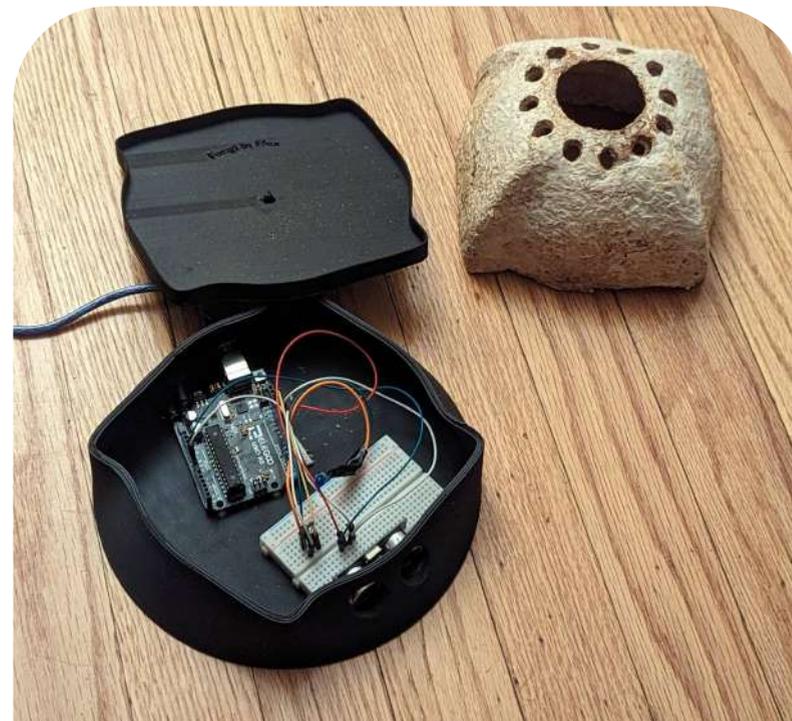
3D printing of a two-part mold with hex-shaped alignment slot



Growth phases of mycelium lampshade



Integration of micro-controller and sensor in the 3D printed base



## Mycelium and Electronics

Myco-Lamp infuses a functional lighting solution while embodying a circular design. It consists of two core components: a lampshade from mycelium and a 3D-printed PLA base housing the electronics. The lampshade leverages mycelium's lightweight yet durable properties, providing an organic texture that diffuses light beautifully. The PLA base serves as the brain. It contains an Arduino micro-controller, an ultrasonic sensor, LEDs, and other electronic components.

Achieving seamless integration between these disparate elements required both the designer's and the engineer's hats. The lamp's geometry and usability requirements guided the design decisions, while the material fabrication and sensing-feedback shaped its engineering aspects. For easy access in potential repairs and recycling, the PLA base was designed modularly, using standard screws and joints for the replacement of electronic components without discarding the entire unit. The ultrasonic sensor imbues the lamp with a degree of interactivity, triggering a change in LED intensity and color based on the distance. This interplay between technology and the organic appeal of the mycelium creates a distinctive experience.

The end-of-life scenario of the product presented a problem, as it is composed of a mix of bio-based and synthetic materials alongside electronic components. Although PLA is a biodegradable plastic, it requires industrial composting plants to break down efficiently, and access to these facilities is limited. Electronic waste recycling can be energy-intensive, and recovering valuable materials from such waste remains a barrier.

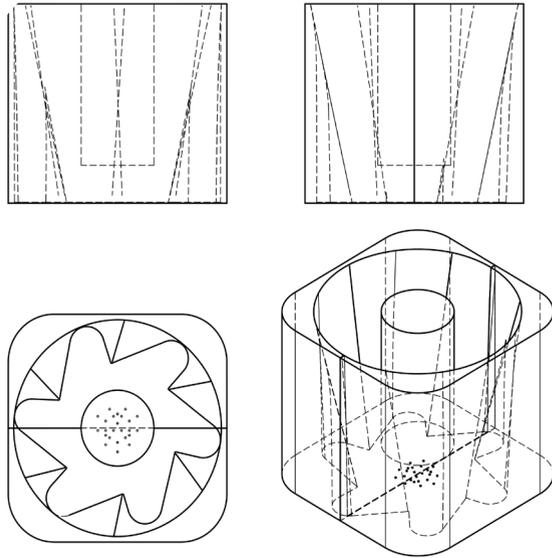
There are inherent challenges and opportunities in creating tech-based sustainable products. Scrutinizing the product's life cycle toward dematerialization may help streamline resources used in the process. Instead of having plastics and metals in the base, an area of improvement lies in seeking universally compostable or recyclable materials, high-performance mycelium compositions, and bio-luminescent and renewable lighting systems that can run on a smaller footprint and enhance the product's repairability, longevity, and overall impact.

CONCEPT II

# Myco-Planter

Mycelium planters are perfect for growing plants indoors and even better outdoors. You can simply place it in soil and let it biodegrade over a few weeks, as the roots grow out.





CAD drawing of mold



Used glass jars and old plastic bottles are used with two parts of the 3D printed mold to reduce the footprint of the process.

The planter can be placed outdoors to gradually decompose over a few weeks.



## Just-in-time Biodegradability

Creating the Myco-Planter involved an innovative fusion of biological and digital fabrication techniques. The mold was 3D-printed in an organic form in PLA, motivated by the criteria to maximize the surface area for mycelium growth and promote better airflow, supported by additional holes at the bottom of the mold. Ventilation is crucial as the proper air exchange ensures healthy mycelium growth through a two-inch thick base and contributes to the structural integrity of the final product.

The cafe's response to the mycelium-based planters was incredibly positive. The staff and customers at Nitro Bar not only admired the organic and earthy texture of the planters, which complemented their indoor plant collection, but they also appreciated its practicality for indoor and outdoor use.

One particular aspect worth mentioning is plant watering. Due to mycelium's porous nature, moisture gets expelled throughout its entire surface, unlike traditional pots that retain moisture. As a result, the plant housed within the mycelium-based material required watering two to three times more frequently to maintain optimal hydration levels.

Additionally, there were technical challenges around maintaining optimal growing conditions for mycelium and controlling the decomposition process once the planter was in use. Overcoming these hurdles requires further experimentation, prototyping, and learning. Looking ahead, the Myco-Planter presents exciting possibilities for just-in-time biodegradability and temporary use.



Myco-planter with water droplets from the moisture after growth phase.



## Organic Furniture for Future Spaces

In furniture design, utilizing mycelium materials presents an opportunity to fabricate lightweight and sustainable components, including table tops, seating, and decorative elements. These materials exhibit a distinctive appeal and textural quality, coupled with their ability to be cultivated close to or on-site, thus enhancing their feasibility as an organic and impactful alternative to conventional materials such as wood. Mycelium materials demonstrate relatively high compressive strength and insulation, rendering them suitable candidates for substituting extractive resources in furniture applications.

This section encompasses various furniture concepts, comprising a mycelium stool, a mycelium repair kit, and a modular seating and storage system. Diverging from prototyping materials, lamps, and planters, the furniture designs featured herein possess the capacity to retain larger quantities of embodied carbon over extended periods. By adopting de-materialization from electronics and circumventing mediums such as soil and water that expedite the biodegradation process, these furniture concepts can endure and preserve their carbon for prolonged durations while disintegrating upon reaching their end-of-life stage.

CONCEPT III

# Myco-Stool

The Myco-Stool, with its fusion of biodegradable mycelium and re-purposed cardboard, re-imagines the humble stool as a sustainable, functional, and artful piece of furniture.





Cardboard scaffold



Sculpted mycelium shell



Mid-growth checkup

## Scaffolding and Structure

The Myco-Stool, like many other myco-products that are discussed, was a culmination of design and biology. Its design revolved around simplicity and structure, crafted entirely from compostable materials to resonate with those seeking eco-conscious products. Inspired by the mushroom shape, the stool's natural, organic form adds a distinct visual appearance.

It uses a combination of cardboard scaffolding sourced from packaging waste surrounded by mycelium. The cardboard provides the necessary support, while the mycelium contributes to the stool's rigidity. The hand-sculpted mycelium grows around the scaffold and results in a durable product capable of withstanding everyday use, while also being capable of naturally breaking down at the end of life.

Achieving the delicate balance between strength and lightweight design required meticulous fine-tuning of the mycelium-to-cardboard ratio and layering. The proposed stool can support up to 100 kgs of vertical loading while maintaining its form.

The Myco-Stool represents a significant step in the concept developments. It showcases the potential of mycelium-based materials to create beautiful and durable products while being made from 100% compostable waste. Educating users about the end-of-life scenario is crucial such the stool can be disposed of appropriately and contribute to the biological cycle.

CONCEPT IV

# Myco- Repair Kit

More than 10 million tons of furniture goes to landfill each year in the United States (EPA). The Myco-Repair Kit extends the life of these objects through adding a natural and durable element to broken or loose parts of old furniture.





Broken leg joint



Myco-repair paste and covering film

## Repair and Value Extension

The Mycelium Furniture Repair Kit breathes new life into pieces that might otherwise be destined for the landfill. This solution is an ecological, innovative, and practical response to furniture waste, focusing on repair and longevity over disposability, recyclability, or biodegradability.

As a filamentous fungus, mycelium naturally binds and forms strong networks, making it an excellent material for mending furniture joints or replacing missing parts. By creating a mycelium paste molded around broken parts, we essentially introduce a 'living glue' that strengthens as it grows.

A mycelium-composite paste is prepared and spread over the broken or missing section of the furniture piece. This paste is then covered with a protective film to provide an ideal environment for mycelium growth. Over a short period, the mycelium binds the pieces together, forming a solid, resilient structure. These repaired furniture pieces can be dehydrated naturally in the sun at 20-30C. Solar or natural drying solves the problem of large furniture not fitting into conventional ovens for drying and, more importantly, minimizes energy consumption, thereby reducing the footprint.

Molding mycelium around complex or intricate designs can sometimes test patience, skill, and care. In tackling these challenges, however, we open up a new understanding of materials and growth, exploring the tension between the organic and the manufactured.

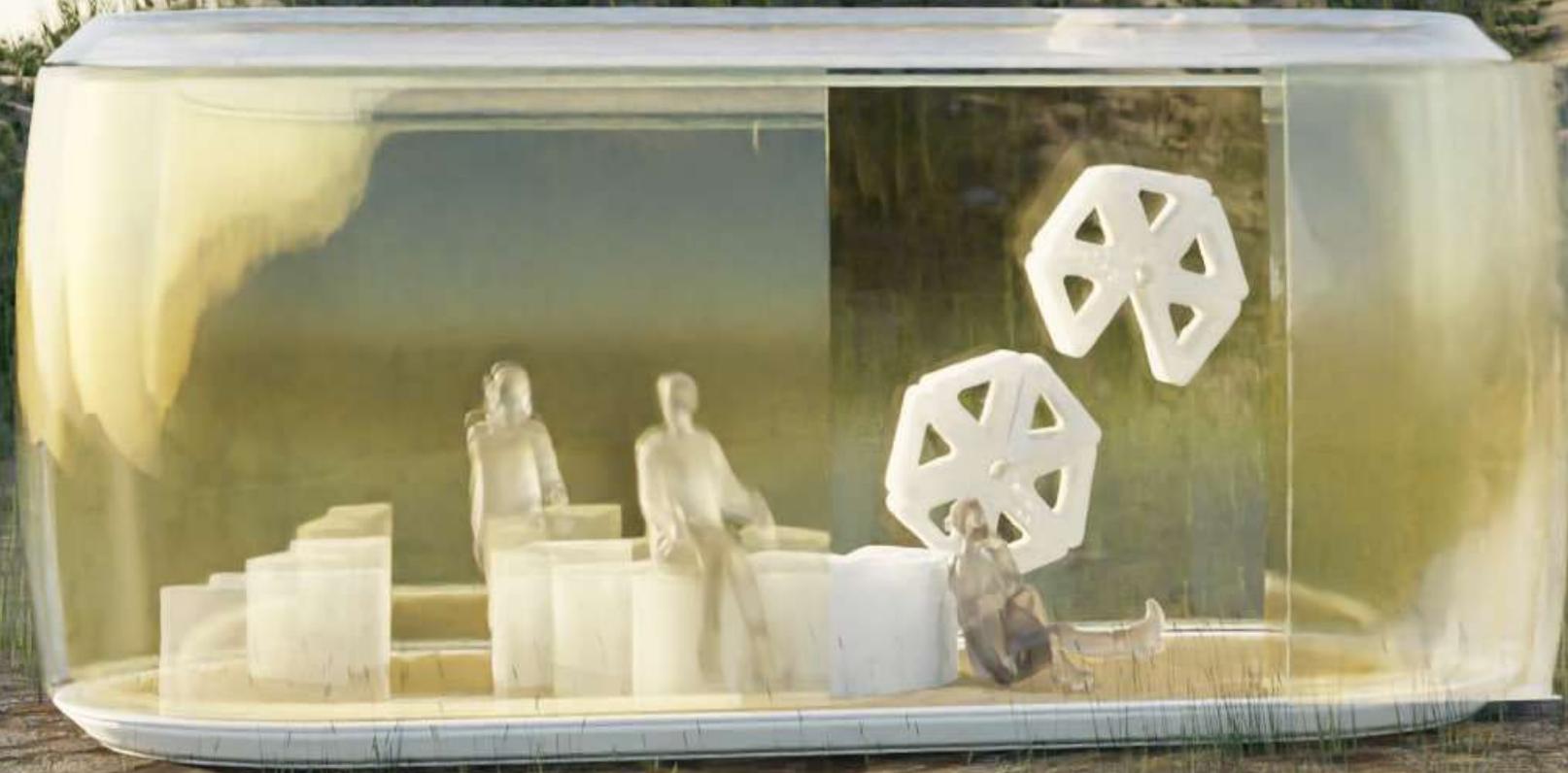
Repaired furniture pieces carry a story, an imperfection made perfect by the miraculous power of fungi. The Mycelium Furniture Repair Kit is conceptually akin to the ancient Japanese art of Kintsugi, which mends broken pottery using lacquer mixed with gold. Where Kintsugi highlights the beauty in the broken and repaired, adding value through gold, our method employs a living organism to transform broken furniture pieces into functional, sustainable, and captivating objects.

Finally, we reflect upon the intricate network of mycelium that holds it together, a hidden, thriving testament to the possibilities of a symbiotic relationship with nature. In a throwaway society, a lesson may be learned here - sometimes, what is broken does not need to be discarded but reborn.

CONCEPT V

# Hex-Mode

This project was supported by Hyundai Motor Group during the 'Future Spaces' course at RISD and Kia Collaborative. For autonomous purpose-built vehicles, the biomimicry question is how might we learn from nature to organize space efficiently?



Hex-Mode concept render for Kia's purpose built vehicles in collaboration with Vaishnavi Mehta



Individual modules function as seats, and can be stacked with other



Three stages of mycelium module growth: cardboard and film, only film and open



## Modularity and Multi-Functionality

HexMode aims for a revolutionary approach to furniture design, drawing inspiration from nature's resourcefulness and previous learnings. This modular mycelium furniture system mimics the brilliance of the honeycomb structure, known for its immense efficiency of enclosing larger spaces using the same amount of wall material.

The primary framework comprises larger hexagonal modules whose design is underscored by honeycombs' intrinsic spatial efficiency and compactness. Nested within each hexagon are six robust modular triangular prisms engineered to double as internal trusses for the hex. This design supports the overall structure with an added layer of stability and strength. Each triangular prism can support up to 100 kgs, demonstrating their dual functionality as standalone seating modules.

The independent triangular prisms can be freely oriented and rearranged, enabling many audiences beyond mere seating. They effortlessly transform into functional tables and convenient storage spaces and can be configured to cater to various spatial needs. This flexibility is key to the adaptability of the system, making it as dynamic as the users' needs in custom environments of the autonomous vehicle in travel, shelter, storage and more.

This concept has been tailored for Hyundai and Kia's Purpose Built Vehicles, envisaging a future of autonomous vehicles. The system aligns with the aspiration for modularity and adaptability in custom environments, delivering a furniture solution and a method for maximizing space utility, fostering interaction, and enhancing passenger comfort.

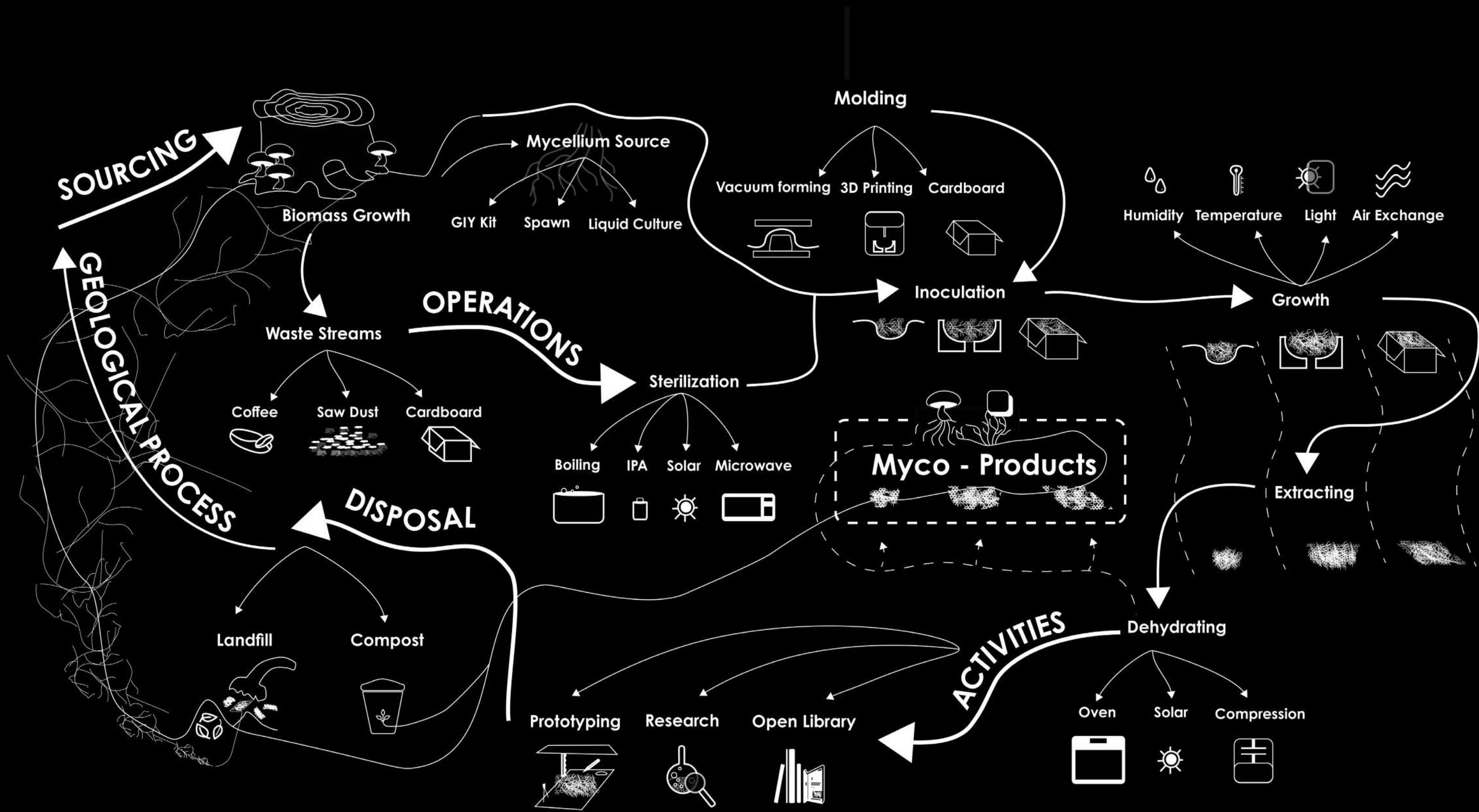
Beyond furniture, mycelium material demonstrates adequate thermal insulation and moisture resistance properties, and it could also find applications in the automotive industry as eco-friendly alternatives to traditional materials. For instance, it could be used for wall insulation, body panels, or flooring systems, resulting in a significant ecological impact.

HexMode extends beyond innovative design and engineering by employing our mycelium process as the core - underlining our commitment to sustainability and to make it an embodiment of future-forward, mycelium design. It is more than just a furniture system. In shaping the future of autonomous vehicles, HexMode may not just fit into our vision of the future - it could actively shapes it.



PART FOUR

# Fostering Systems



## Flows and Mapping

Analyzing system flows within a mycelium materials system is vital in creating an accessible, robust, and efficient system. Considering the microsystem's carbon footprint and carbon sequestration potential, it becomes especially significant. The flows encompass the movement and transformation of resources within a defined system, from raw materials to the end-of-life stage.

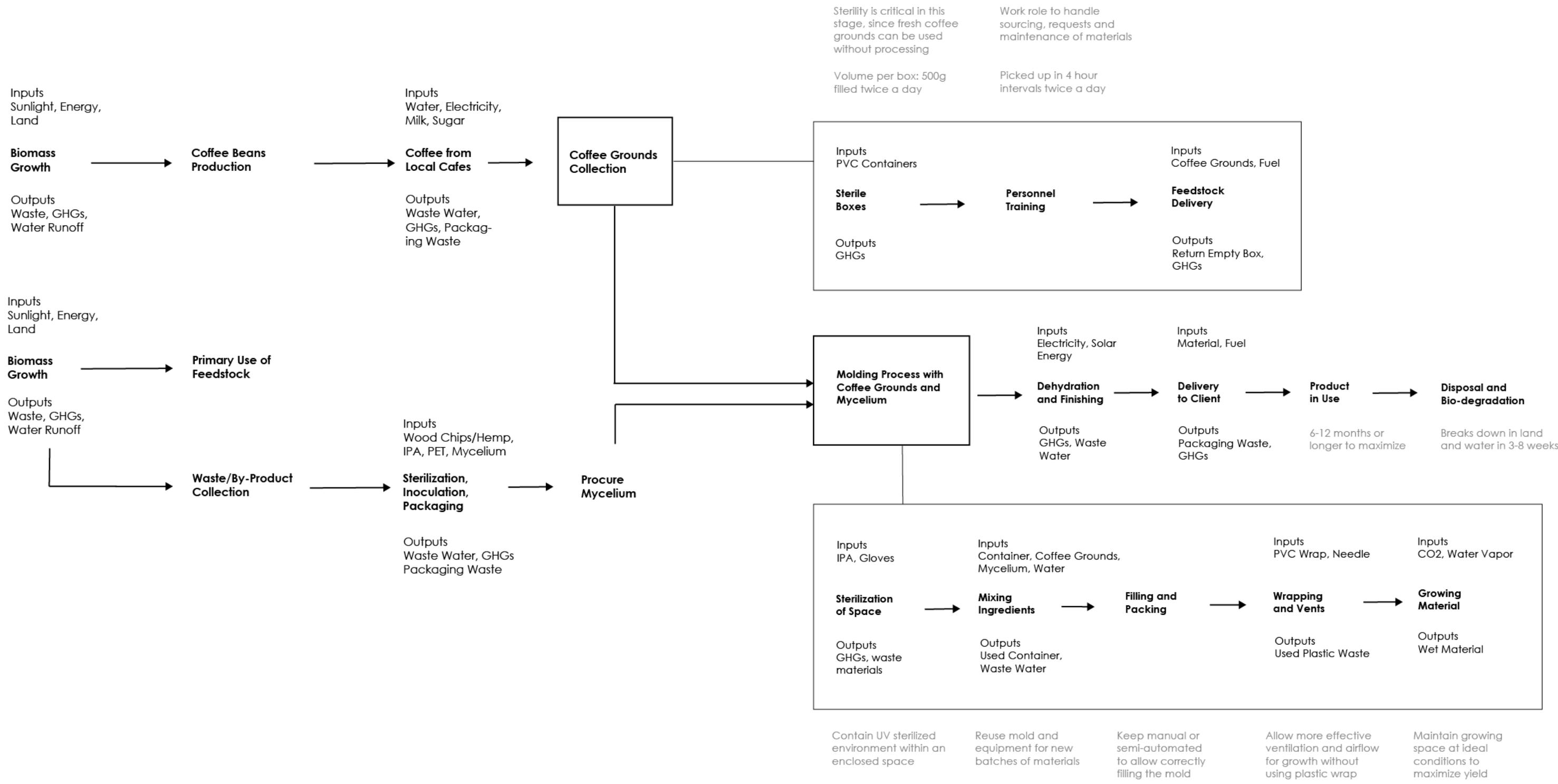
Overall, it includes materials, energy, human resources, and capital, all entwined within our complex, often destructive socio-economic system. Given the existing dependency on traditionally harmful sources, processes, and infrastructure for the climate and humanity, designing endemic ecosystems from a sustainability perspective becomes crucial.

Several methods exist to map these flows, including using Sankey diagrams, which visually represent the different flow magnitudes within a system. Material flow analysis (MFA) is another approach, systematically assessing material flows and stocks within a temporally and spatially defined system.

Creating a frugal material system can lessen dependencies and reduce process impacts. Achieving this includes selecting equitably sourced ingredients, tools, and utilities. Positioning raw material collection and production locations closer can reduce transportation needs. Shifting high energy consumption stages of the operation, such as sterilization and dehydration, to renewable sources like solar energy can further improve the system's sustainability.



Mapping mycelium systems



## Materials

When enhancing the sustainability of mycelium bio-fabrication, an essential strategy is opting for non-toxic and biodegradable materials whenever feasible. This not only strengthens the low-footprint nature of the process but also contributes to our safety and health by protecting environments.

Sources: Substrate procurement needs to prioritize disruptive, abundant and local waste specific to contexts. For mycelium, a preferred option over Grow-it-yourself (GIY) kits and liquid cultures are more affordable spores or spawn, for a lower ecological footprint.

Mold: Sustainable mold design entails creating low-footprint reliable components for easy disassembly. 3D printed PLA for reusable molds, and cardboard as low-impact biodegradable molds reduces costs, minimizes environmental impacts, and diverts process waste from landfills.

Tools and Containers: Adopting sterilizable and reusable containers like glass or stainless steel jars and common household items as workspace tools and containers promotes a convenient, accessible and sustainable model.

## Energy

In parallel with optimizing material resources, it is imperative to implement energy-efficient and passive methods for processes. This maximizes energy conservation, reduces reliance on non-renewable sources, and contributes significantly to the overall reduction of the footprint of the fabrication process.

Growth: Adopting strategies such as passive solar heating or evaporative cooling for maintaining temperature and humidity, or adapting the growth environment to align with local climate toward resource availability.

Sterilization and Dehydration: Incorporating energy-efficient methodologies for substrate sterility and dehydration, solar sterilization and drying boosts the resilience of the mycelium bio-fabrication process.

Transport: The main recurring material flow comes from raw material collection and transportation of finished goods. At the current design scale, where the collection site is a 100 meters from the lab, daily material transportation on foot amounts to zero net emissions.

## Resilience

Establishing a resilient workspace means designing an adaptable, modular environment that flexibly accommodates various material needs and requirements. This modularity ensures that the space can evolve with the changing demands of the biofabrication inputs and processes, thereby maintaining productivity and reducing downtime during transitions.

## Efficiency

Efficiency involves implementing practices that minimize waste and optimize resource usage. It involves precise measurement and controls, management of inventory, actively seeking to reduce by-product generation and an optimal network arrangement of flows.

## Access

The process becomes more accessible and affordable when low-cost, locally sourced waste materials are used. An open-source library of materials, educational workshops, courses, and exhibits can be established to engage the broader public, thereby democratizing the knowledge and potential of mycelium bio-fabrication.

# Lifecycle Assessment Model

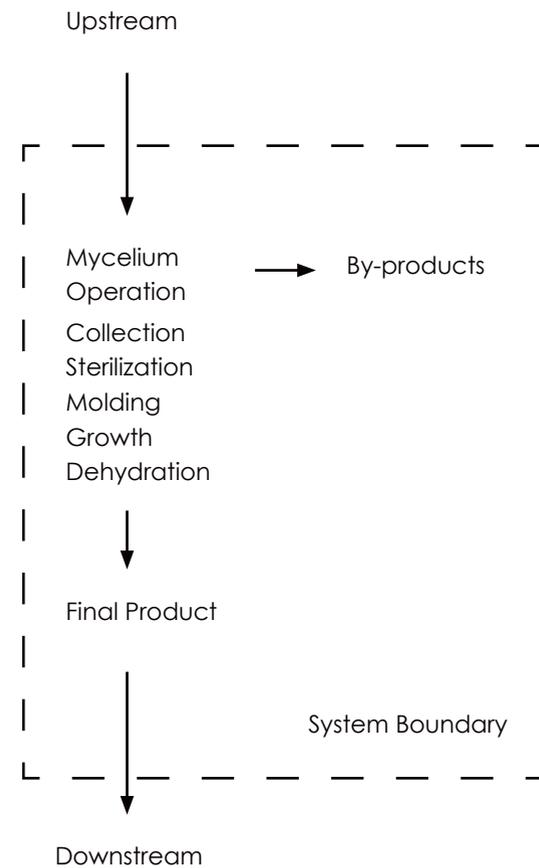
Life Cycle Assessment (LCA), quantifies system flows and evaluates environmental impacts across a product's life cycle - from extraction, processing, manufacturing, distribution, usage, repair, and maintenance to disposal or recycling, effectively from cradle to grave. This study zeros in on the production stages of mycelium bricks for a carbon-impact calculation.

To ascertain mycelium's footprint, we have chosen the 'allocation at the point of substitution' system model. This model assigns environmental burdens to the system based on material or energy flows, thereby addressing the direct impacts of our process. It enables us to gauge the carbon emissions from our production process and those potentially saved when our product supplants a more carbon-intensive alternative, such as plastic.

The boundary conditions for this LCA encompass the processes directly implicated in producing mycelium bricks, including sawdust collection, blending with mycelium and water, sterilizing, growing and dehydrating the material. We have chosen not to include indirect systems such as equipment manufacturing or biomass production because of limited and inaccurate data. As a frugal setup, our system maintains a narrow scope.

## Assumptions

- The carbon emission factor for electricity generation in Rhode Island is roughly 0.40 kg CO<sub>2</sub>/kWh (US EPA)
- The HVAC system's calculation considers only the winter season, the length, severity and efficiency of which may fluctuate based on geography.
- The zero-carbon strategy for sterilization and dehydration rests on a region's capacity to tap into ample solar radiation throughout the year.



Simplified Lifecycle Assessment Model and Boundary

# Carbon Calculations

For these calculations, we consider a batch of 100 mycelium bricks per two-week cycle, and 2600 annually.

## Carbon Footprint

**Water:** Every mycelium brick requires 200 ml of water, leading to an annual usage of 52 cubic meters considering the production of 2,600 bricks. Taking the CO<sub>2</sub> footprint of water, which is 0.344 kg CO<sub>2</sub>/m<sup>3</sup> (Water Research Foundation, 2021), the total annual CO<sub>2</sub> emissions from water are 17.88 kg.

**Molding:** The process needs 0.5 grams of PVC film for each brick while the molds are reusable. Given that the CO<sub>2</sub> equivalent of PVC is roughly 3.3 kg CO<sub>2</sub>e/kg PVC (PlasticsEurope, 2018), the total annual CO<sub>2</sub> equivalent due to PVC film usage for 2,600 bricks calculates to 4.29 kg of CO<sub>2</sub>e.

**Growth:** A small fan and humidifier to maintain the environmental conditions is estimated to consume about 200 kWh/year, considering it operates 12 hours per day for six months (Energy Use Calculator, 2021). Applying the average carbon emission factor of 0.40 kg CO<sub>2</sub>/kWh, the total carbon emissions would be 80 kg CO<sub>2</sub>/year.

Given these factors, the annual carbon footprint for the production of 2,600 mycelium bricks is 102.178 kg of CO<sub>2</sub>.

## Carbon Capture

The main components of our bricks are mycelium and sawdust, which contain a significant proportion of carbon at a molecular level.

Mycelium primarily comprises chitin, a polymer whose fundamental structural unit, N-acetyl-D-glucosamine, C<sub>8</sub>H<sub>13</sub>NO<sub>5</sub> (Ji et al., 2006) where carbon constitutes 44.44% of chitin by mass. Given that the biomass of mycelium is largely chitin, we can leverage this figure to estimate its carbon content.

Similarly, sawdust primarily comprises cellulose, hemicellulose, and lignin, all carrying a considerable carbon content. The chief component, cellulose, with the molecular formula C<sub>6</sub>H<sub>10</sub>O<sub>5</sub>, also contains approximately 44.44% carbon by mass (Fengel & Wegener, 1989).

Assuming a 300g brick consists of equal parts sawdust and mycelium, it contains approximately 133.32g of carbon. Over the course of a year with 2,600 bricks, this equates to 346.64 kg of carbon.

To convert this to the equivalent CO<sub>2</sub> captured, we consider the molar masses of carbon (12.01 g/mol) and CO<sub>2</sub> (44.01 g/mol). As the mass of CO<sub>2</sub> equivalent is about 3.67 times the mass of carbon, the bricks would capture 1,272.82 kg of CO<sub>2</sub> equivalent annually.

## Results and Insights

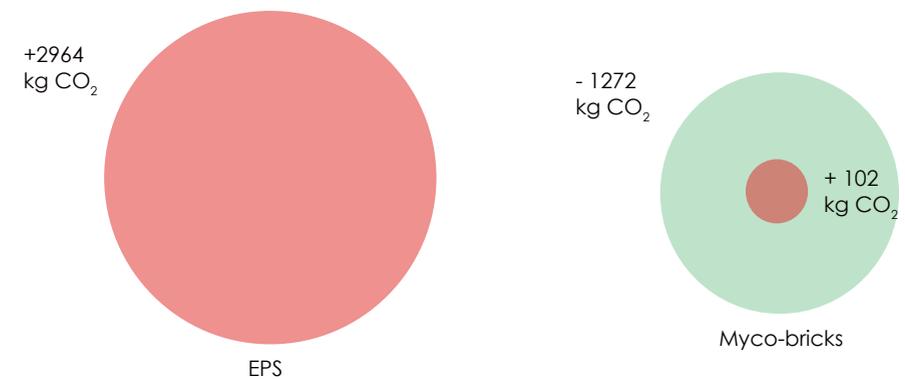
Taking into account the carbon footprint and carbon sequestration data, the estimated annual CO<sub>2</sub> emissions from the production of mycelium bricks are 102.56 kg CO<sub>2</sub>. Meanwhile, the annual CO<sub>2</sub> capture of the bricks is approximately 1,272.82 kg. A net annual CO<sub>2</sub> absorption of around 1,170.26 kg, positions the mycelium bricks as a carbon-negative material.

Contrasting our net carbon footprint calculation with traditional plastic materials, a striking difference becomes evident. Expanded Polystyrene (EPS), a plastic foam material, has a carbon footprint of about 3.8 kg CO<sub>2</sub>e per kg (Plastics Europe, 2015). Assuming an equivalent volume and density, a brick of EPS with the same mass as our mycelium brick, would result in an annual total of 2964 kg CO<sub>2</sub>e. The shift from EPS to mycelium bricks leads to a significant reduction in emissions and an active contribution to carbon capture.

## Scope

These figures may only sometimes hold, and actual values could vary based on the precise composition of the bricks, efficiency of carbon capture, and lifecycle stage of the mycelium. In addition, some processes that yield zero or negligible emissions in this analysis due to their localized, manual, or renewable nature, such as material collection and brick dehydration, may not scale proportionately as operations expand. For instance, the carbon footprint could increase if transportation involves vehicles, or sterilization and dehydration become energy-intensive.

While these calculations provide quantifiable benefits of mycelium materials, they also recognize the need to think beyond carbon, toward of ocean acidification, deforestation and biodiversity loss among others ecological factors. Well-informed sourcing, well-performed processes and well-planned disposal can minimize emissions and maximize sequestration.



# Concluding Thoughts

This journey through understanding materiality, exploring mycelium, and growing organic products has been one of the most enriching and insightful experiences. By investigating the nature of materials, the complexities of ecological systems, and the potential of mycelium as a sustainable material in design, this research hopes to contribute to a broader design vision for bio-futures. By developing a strategic framework with core values of resilience, efficiency, and access and applying it to a mycelium biofabrication and biodesign process, this research demonstrated the significance of these principles in guiding our approach.

Designing for resilience, we can create flexible systems in the face of external changes: resource availability, adaptation to varied inputs, and diverse locations. Efficiency was crucial in optimizing the use of limited resources and minimizing waste: aimed at closed-loop systems, creating streamlined processes, and leveraging technology. Finally, open access let the community participate in and collectively benefit from materials design and development, promoting physical, ecological, and information sharing.

From a biological-to-industrial perspective, this project worked with the unique properties of mycelium as a living resource. It drew inspiration from science, design, and engineering, emphasizing the importance of understanding and harnessing fungi's biology, intelligence, and material ecology. By integrating these principles into the design of materials and products, the project attempted to create a material ecosystem informed by nature and one that contributes to a biologically circular economy. It explored the creative possibilities for biodegradable, environmentally friendly products and processes. Investigations in mycelium's mechanical and experiential characterization showed how small-scale workspaces can produce myco-materials in custom forms and with varying properties and function as a multi-use resource for material experimentation and production.

A suitable composition of sawdust or coffee grounds is formulated through experiments for variables in mycelium species, waste streams, and growth conditions. A summary of results from various experiments and tests in this thesis are listed below:

- Determination of optimal parameters and conditions for mycelium growth, such as a temperature of 25 to 30 °C, humidity levels of 70% to 90%, along with molding techniques using cardboard, 3D printing, and vacuum forming.

- Qualities of mycelium growth, such as surface layer thickness, increased from 0.1mm to 2mm in a multi-stage growth process, contributing to the material's structural integrity.

- Material characterization of mycelium composites yielding compressive strength values in the 0.17 to 0.46 MPa range, 177 to 542 g/cm<sup>3</sup> density, and water absorption rate of 130 to 190%.

- Experiential characterization in workshops quantified and visualized user perceptions of mycelium materials, with 62% of participants requesting samples of the material for prototyping use.

To promote the use of sustainable materials and practices on a larger scale, we form partnerships with academia and industry, design biodesign curricula and workshops that examine the lifecycle of products, and encourage responsible choices by changing perceptions. Additionally, we foster a culture of collaboration and innovation by sharing designs and fabrication techniques, providing resources and support for mycelium cultivation and experimentation. Making these techniques and our research data accessible through a platform like [fungiinflux.com](https://fungiinflux.com) is a step towards democratizing mycelium. Sharing innovative methods and techniques hopes to develop a platform that is available to a wider audience in broader contexts.

Finally, we acknowledge that pursuing mycelial bio-futures requires an approach considering the complexity of climate, biology, and industrial systems in our design practices. In doing so, we may safeguard our planet's biodiversity and ecosystems and secure a healthy, and prosperous future for humanity. This research is just one small step in that journey, but every step brings us closer to a sustainable and regenerative future for all.

# Community and Website



# Exhibitions



Sol Koffler Gallery,  
Providence, March 2023





Rhode Island Convention Center,  
Providence, May 2023



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