Living Mycelium

A Generational Shift from Blocks to
Unbounded Living Architecture

by
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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis including any required final revisions as accepted by examiners.

I understand that my thesis may be electronically available to the public.

Abstract

The thesis explores the emerging realm of “living” fungal-based composites in architecture, examining a shift from methods that form and dry mycelium (fungi's rootlike networks,) - referred to here as "nonliving", to methods based on mycelium's unique growth processes, referred to here as "living". By utilizing the biological functions of mycelium in its living state, this generation of living methodologies addresses the challenges and limitations faced by earlier mycelium applications and further advances the potential of mycelium in the construction and architecture industry.

For the past decade, there has been a growing interest in the bio-fabrication of mycelium due to its sustainable, structural, and economic benefits. Claimed as one of the leading classes of biomaterials, mycelium-based composites building material alternatives that promote low-carbon emission and are compostable. Despite gaining recognition, the integration of mycelium in architecture remains limited, with the composite mostly applied to installation and exhibition scale projects. By drying and killing the organism, the predominant brick-and-panel approach of mycelium research of the last decade has tended to fix mycelium in the shape of a given formwork rather than privilegling mycelium's unique growth capacities. Earlier research on using mycelium in construction relied heavily on traditional construction methods and replicating conventional materials without fully utilizing its capability for self-healing, self-growth, and self-organization.

By analyzing five case studies that reflect this generation of recent "living" mycelium research, this thesis aims to demonstrate the benefits of preserving mycelium in its living state to translate their innovative methodologies to mainstream architecture applications. Specifically, the thesis investigates five strategies and illustrative mycelium research projects that foreground mycelium’s unique biological properties in its living state: Myco-welding of conventional mycelium-based blocks (*La Parete Fungina*), Fibre reinforcement and welding of 3D-printed components (*Mycera*), Bio-collaboration of mycelium-based composite and bacterial cellulose (*BioKnit*), Bio-tectonic of living mycelium (*Mycelium Tectonics*), and Senso-aesthetics of mycelium’s natural processes (*Mycelium Rope*).

The thesis identifies three key characteristics of this generation of research across these projects: 1. biological utilization (the active harnessing of mycelium's unique biological processes), 2. integral and lost formwork (the use of formwork that becomes a permanent part of the structure), and 3. material understanding and visual acceptance (the understanding of technical knowledge and aesthetic appreciation of mycelium as a building material) . Each case study's research goals, design intentions, methodologies, and reflections will be explored to provide insights into the potential of living mycelium architecture. The concepts presented in the paper challenge traditional notions of today’s static architecture and propose a dynamic and living framework capable of adapting to its environment. The study positions living mycelium as a model for resilient and adaptive structures. This approach offers new insights for sustainable construction that harness the self-repairing, regenerative properties of living organisms. The purpose of this comparative research is not to undermine the existing development of non-living mycelium architecture but rather to expand the knowledge of the unique natural functions of living mycelium toward sustainable design practices.

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To my parents, thank you for the sacrifices you've made and the lessons you've taught me. This accomplishment is not just mine, but ours, and I couldn't have done it without you.

Dedication

To my father,
the one who sparked my passion
for architecture and design.
This work is for you,
I hope I've made you proud up there.

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Chapter 1: Introduction



1.1 Mycelium Marvels: The Living

"Despite the sustainable, economical, and structural benefits, there is an inherent problem in using fungal-based materials simply as an alternative to standard building materials. The problem with this approach is that fungus-based materials retain the assembly techniques of their traditional counterparts. Fungal-based bricks are stacked in the same way as conventional bricks; they require just as much labour and just as much mortar. A new method of construction could emerge simply by leaving the fungal bricks alive during assembly, rather than killing the organism..."[1]

-Sean Campbell et al.

As Sean Campbell *et al* wrote in the quote above, designers tied to the building sector share an essential duty in reducing the use of non-renewable natural resources as a global sustainable strategy. In response, the use of bio-based materials or biomaterials has gained popularity in the construction industry (see figure 1.1). Alongside the emergence of relatively well-known bioplastics such as Poly-Lactic Acid, there has been a great interest in fungal-based materials, driven by the biological properties of fungi's root network, mycelium.[2] Recent developments of renewable mycelium-based composites have offered a tremendous amount of potential in different industries such as furniture, packaging, fashion, and most notably, construction.[3] Amongst the forty-seven academic papers from 2012 to 2019 that focus on the relevance of mycelium in architecture and design, the literature review observes the production of bricks or blocks mycelium-based composites as the most common approach for building material alternatives.[4] These composites are commonly grown in custom-made moulds, eventually dried in ovens, and transported to site for assembly. Typically, these bio-bricks and blocks are applied with the same principles of brick, while in some cases, require assistance from temporary formwork and scaffolding structures.[5]

A personal realization from the qualitative research of mycelium architectural projects is the significant generational shift from using inanimate materials to adopting a living growth process approach (see figure 1.2). Reflecting on the short excerpt above, designers in art and architecture industry noticed that most mycelium architectural projects view mycelium-based materials simply as alternatives without the consideration of the complex hyphae network's numerous biological

1. Sean Campbell et al., "Modular Mycelia: Scaling Fungal Growth for Architectural Assembly," 2017. 2

2. Dimitra Almpani-Lekka et al., "A Review on Architecture with Fungal Biomaterials: The Desired and the Feasible," Fungal Biology and Biotechnology 8, no. 1 (November 19, 2021): 2, https://doi.org/10.1186/s40694-021-00124-5.

3. Selina Bitting et al., "Challenges and Opportunities in Scaling up Architectural Applications of Mycelium-Based Materials with Digital Fabrication," Biomimetics 7, no. 2 (April 14, 2022): 2, https://doi.org/10.3390/biomimetics7020044.

4. Noam Attias et al., "Mycelium Bio-Composites in Industrial Design and Architecture: Comparative Review and Experimental Analysis," Journal of Cleaner Production 246 (February 10, 2020): 2, https://doi.org/10.1016/j.jclepro.2019.119037.

5. Attias et al., "Mycelium Bio-Composites in Industrial Design and Architecture." 3



Fig. 1.1. Application of biomaterials in construction as insulation, panels, and floor tiling.



Fig. 1.2. A zoomed in image of mycelium's unique natural behaviour in the project, *Mycelium Tectonics.*

properties.[6] More recently, mycelium architecture researchers have adopted sustainable material approaches that adopt pure biologically inspired systems. Exploring the capabilities of mycelium alive allows designers to envision waste-free production of structurally optimized, organic forms that embody unique formal expressions as compared to standardized, mass-produced forms typical of industrial manufacturing.[7] Thus, newly published experimental works of mycelium in architecture that include research experiments and student works display a shared goal of fully utilizing mycelium in its living state to open the discussion of mycelium's natural systems' potential in architecture alongside the conventional, nonliving approach of bricks and panels.[8] While the more commonly applied method of bricks and panels provides additional level of control and consistency to produce architecturally viable works, it overlooks the fungi's biological properties of self-organized growth and potential to challenge today's conventional construction methods.[9] The brick-and-panel approach of moulding mycelium-based composite, while straightforward and suitable for industrial-scale production, limit the end-product's geometrical complexity and customizability.[10]

As researchers and designers show more interest in adopting the specialized approach of living mycelium, the compelling and multifaceted results of the living mycelial approach become more evident. Natural systems acquire unique functions of adaptation, resilience, self-repair, self-organization, and self-growth that are not present in current construction components. The natural systems provided by living mycelium offer potential benefits for economical and sustainable architecture as they use less energy in product manufacturing and reuse organic wastes.[11] Thus, this research explores the emerging concept of the "living" mycelium in the context of architecture, identifying and reviewing selected projects that exhibit biological utilization of mycelium in contrast to conventionally killing the organism through a drying process. This research aims to explore the less-viewed lens of living mycelial architecture to give it more legibility. Implying a rethinking of architectural principles, the paper aims to answer the question of how this redefining approach of living processes influences the understanding of space and structure, as well as the boundaries between the built environment and nature. Furthermore, this research seeks to critically evaluate the effectiveness of the specified living approach and reflect on whether the methodological shift could offer greater potential or enhance the current understanding of mycelium in the construction sector.

6. Campbell et al., "Modular Mycelia." 2

7. Eliza Biala and Martin Ostermann, "Mycostructures—Growth-Driven Fabrication Processes for Architectural Elements from Mycelium Composites," Architecture, Structures and Construction 2, no. 4 (December 1, 2022): 518, https://doi.org/10.1007/s44150-022-00073-6.

8. Campbell et al., "Modular Mycelia." 2

9. Ibid. 2

10. Alale Mohseni et al., "Three-Dimensional Printing of Living Mycelium-Based Composites: Material Compositions, Workflows, and Ways to Mitigate Contamination.," Biomimetics 8, no. 2 (June 1, 2023): 3, https://doi.org/10.3390/biomimetics8020257.

11. Campbell et al., "Modular Mycelia." 4

1.2 Mycelium Architecture in the Context of Environmental Crisis

Emergence of a Field

Founded in 2007 by Eben Bayer and Gavin McIntyre, graduates in Mechanical Engineering and Innovation Design (Rensselaer Polytechnic Institute), the company Ecovative is considered a pioneer in research development of mycelium bio-fabrication. Ecovative's early works focused on mycelium-based materials as surrogates for replace petroleum-based Styrofoam such as polystyrene, polyethylene, or polypropylene, all considered non-sustainable. The newly developed packaging alternatives made from mycelium have three beneficial qualities, they are biodegradable, bio-based, and high protection qualities.[12] Another leading figure in the advancement of mycelium-based materials is designer and scientist Philip Ross. In 2009, Ross, alongside his long-time artistic collaborator Sophia Wang, launched a pioneering material research company, MycoWorks, and coined the term Mycotecture that initiated the movement of art of designing and building with mycelium. Ross and the team of MycoWorks' mycelium installations and artworks have been publicly exhibited at international events such as MoMA and The Moscow Biennale of Contemporary Art.[13]

Taking inspiration from the works of Ecovative and MycoWorks, mycelium-based materials started gaining traction in the design industry over the past three decades. Extending from packaging products and insulations, MyCoPlast, founded in 2015 whom recently



Fig. 1.3. Aniela Hoitink's dress made out of disc-shaped mycelium pieces.

12. Elvin Karana et al., "When the Material Grows: A Case Study on Designing (with) Mycelium-Based Materials" 4, no. 2 (2018).

13. "Home," MycoWorks, accessed September 12, 2023, https://www.mycoworks.com/.



Fig. 1.4 MycoWork's self-supporting structure made of mycelium-based bricks, *Mycotecture Vault*.

14. Attias et al., "Mycelium Bio-Composites in Industrial Design and Architecture." 2

15. Ibid. 2

16. Ibid. 3

configured as Mogu, currently develops eco-friendly alternatives for interior and product design applications, mainly focusing on acoustic tile panels and flooring materials.[14] In 2016, the Fungal Futures exhibition held in Netherlands showcased some aspects of mycelium at the intersection of design and science. A few explorative design projects included 3D printed biodegradable scaffolding for mycelium-based furniture by Erik Klarenbeek, an organically formed textile consisting of grown mycelium on mats by Aniela Hoitink (see figure 1.3), and *Mycotecture Vault*, that consisted of mycelium-bricks stacked in a brick-and-mortar manner by MycoWorks (see figure 1.4).[15] Mycelium as an insulator also garnered interest from the construction industry because of its lightweight, foam-like material. Elise Elsacker, a researcher in the Department of Bio-Engineering Sciences at Vrije Universiteit Brussel, opened the discussion of the potentials of mycelium-based composites as alternatives to conventional insulation materials including rock wool, glass wool, kenaf, and sheep-wool plates. After a thorough technical analysis, Elsacker presented a summary of the thermal conductivity and density of mycelium insulation comparable to the products mentioned above.[16]

Fungal Cultivation for Architecture

It is essential to have the basic knowledge and understanding of fungi, or mycelium to be specific, as a learning foundation in investigating the growing scene of cultivated architecture. Whether it is recognized or not, fungi are everywhere (see figure 1.5). Humans walk upon the habitat of the world's largest networks and connections that occasionally run above the surface, commonly known as mushrooms. Figure 1.6 shows a complete overview of fungi life cycle and its relation to the natural carbon cycle. Fungal species are ubiquitous eukaryotic microorganisms that exhibit an enormous diversity in morphology and lifestyle. Mycelium is the network of interwoven, thread-like fungal hyphae and constitutes the vegetative part of fungi. The complex network of mycelium consists of the developmental unit of fungi, the hypha, which grows through the extension and branching of their hyphae into substances.[17] Fungi require nutritional intake from their surrounding environment to branch out, and mycelium takes charge of this action. The hyphae networks of mycelium break down biological polymers of dead matters into simpler molecules and convert them into soluble nutrients, which are often difficult for plants and decomposers to digest.[18]



Fig. 1.5. A zoomed in image of mycelium present in soil.

17. Karana et al., "When the Material Grows: A Case Study on Designing (with) Mycelium-Based Materials." 3

18. Mohseni et al., "Three-Dimensional Printing of Living Mycelium-Based Composites." 2

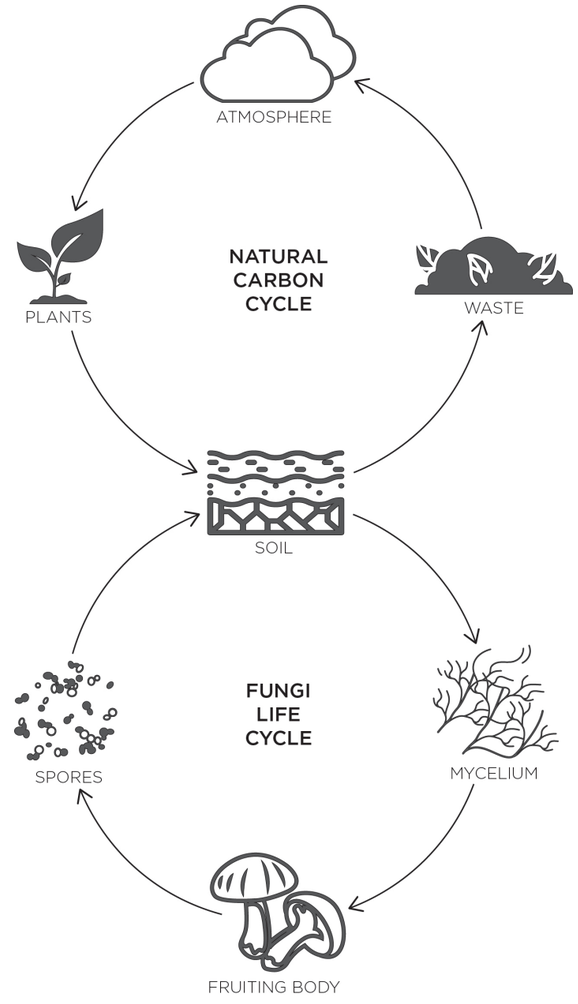


Fig. 1.6. The relationship between fungi's life cycle and the natural carbon cycle

19. Ibid. 3

20. Elise Elsacker et al., "A Comprehensive Framework for the Production of Mycelium-Based Lignocellulosic Composites," Science of The Total Environment 725 (July 2020): 2, https://doi.org/10.1016/j.scitotenv.2020.138431.

As living microorganisms, fungal species react to their environmental conditions through the rebuilding of their mycelium networks to optimize nutrient absorption. They constantly transform, depending on the influences of their environments, thus resulting in varying properties across the mycelial structure.[19] Many fungal species play a vital role in the ecosystem by degrading biomasses and circulating carbon. Due to their physiological and metabolic properties, designers saw their large biotechnological potential as they are likely to provide efficient, resilient, and cost-effective solutions in today's environmental crisis.[20]

Why Mycelium Architecture Now?

While mycelium composites may seem like a marginal or niche material for construction, their potential for material circularity has drawn a lot of research interest. Based upon the review of published articles, researchers have shared their reasoning as to why mycelium could be worth investing time in. One of the primary drivers of the research on mycelium-based materials is its role in closing the loop in today's conventional construction cycle. Evident in the diagram shown in Figure 1.7, the current construction cycle practices a linear approach that views construction as a process of eventually leading to waste. Mycelium-based composites allow for local growing and do not rely heavily on resource extraction, which eventually lowers the demand for long-distance transportation.[21]

21. Matthias Leschok and Benjamin Dillenburger, "3D Printed Formwork for Mycelium Bound Composites," 2023. 3

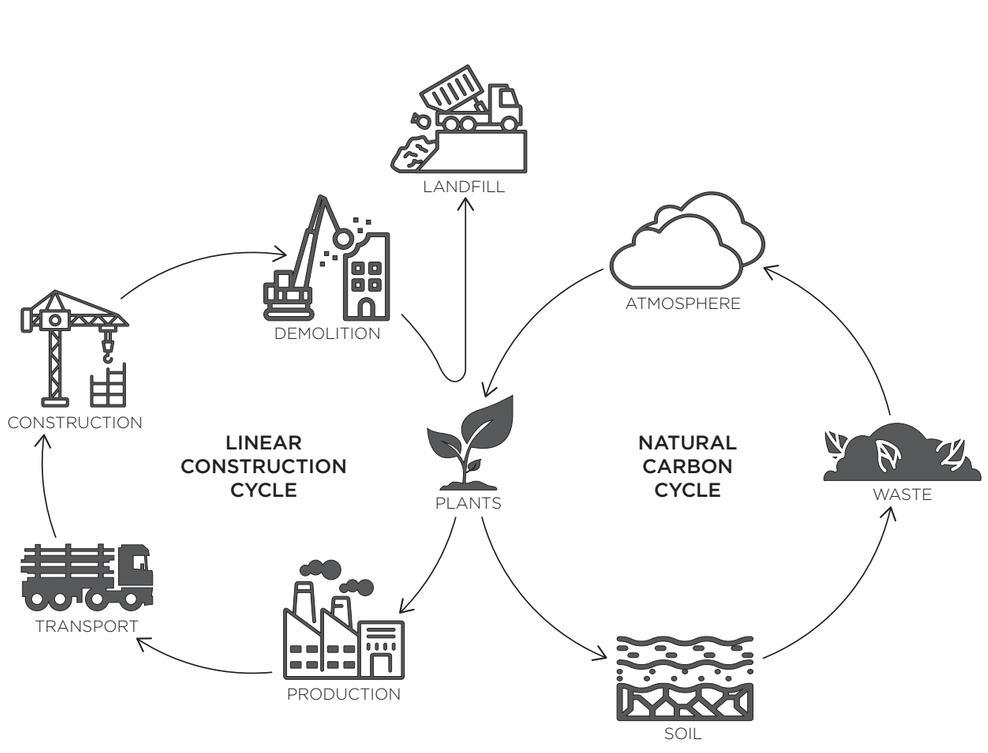


Fig. 1.7 The linear effect of conventional construction in the natural carbon cycle.

22. Mitchell Jones et al., "Engineered Mycelium Composite Construction Materials from Fungal Biorefineries: A Critical Review," Materials & Design 187 (February 1, 2020): 2, https://doi.org/10.1016/j.matdes.2019.108397.

23. Sehrish Manan et al., "Synthesis and Applications of Fungal Mycelium-Based Advanced Functional Materials," Journal of Bioresources and Bioproducts 6, no. 1 (February 1, 2021): 2, https://doi.org/10.1016/j.jobab.2021.01.001.

24. Jones et al., "Engineered Mycelium Composite Construction Materials from Fungal Biorefineries." 3

25. Achiya Livne et al., "Fungal Mycelium Bio-Composite Acts as a CO2-Sink Building Material with Low Embodied Energy," ACS Sustainable Chemistry & Engineering 10, no. 37 (September 19, 2022): 1, https://doi.org/10.1021/acssuschemeng.2c01314.

26. Mohseni et al., "Three-Dimensional Printing of Living Mycelium-Based Composites." 1

27. Livne et al., "Fungal Mycelium Bio-Composite Acts as a CO2-Sink Building Material with Low Embodied Energy." 1

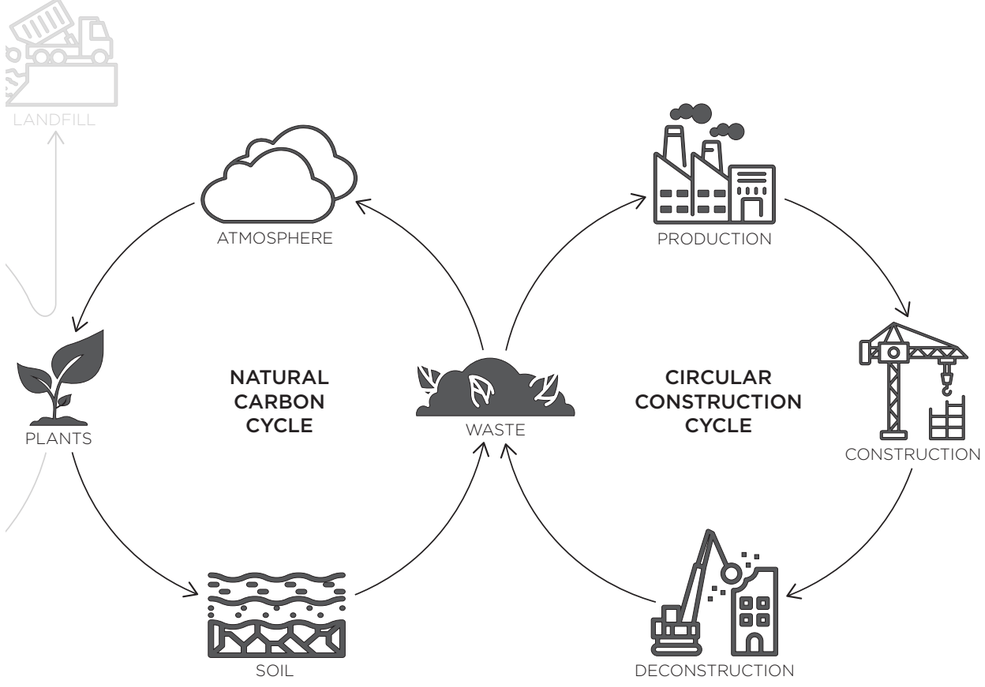
28. Matthias Leschok and Benjamin Dillenburger, "3D Printed Formwork for Mycelium Bound Composites," 2023. 3

29. Jonathan Dessi-Olive, "Strategies for Growing Large-Scale Mycelium Structures," Biomimetics 7, no. 3 (September 2022): 1, https://doi.org/10.3390/biomimetics7030129.

In addition to being grown locally, the production process of the materials is considered eco-friendly due to the valorization of organic waste such as straw or sawdust, as their primary substrates. The wide variety of substrates coupled with the processing methods allow the biomaterials to achieve specific structural and functional requirements such as thermal, acoustic, and fire resistance. It not only replaces synthetic planar materials and low-density objects but also semi-structural materials such as flooring, furniture, and paneling.[22] The materials are comprised of multiple biocompatible components, creating a circular construction cycle as they biodegrade at their end of life.[23] Another advantage of mycelium-based materials is their vital role in the environment's carbon cycle. The manufacturing of the materials uses low-energy and natural processes in which carbon sequestration occurs, a unique property offered by fungi not commonly found in other classes of biomaterials.[24] In a study published by Livne that focused on the carbon influences of mycelium in the environment, the embodied carbon of mycelium-based composites was calculated at -39.5 kg CO_2eq indicating the effective function of the material as a carbon sink for its negative value, in contrast to conventional building materials that acquire positive values. The total processing energy consumption of myco-bricks was also estimated at values that show reductions in carbon emissions as compared with that of common construction materials such as steel and concrete.[25]

According to a study conducted by the United Nations Environment Programme, the building construction industry is responsible for 36 percent of global energy use and 39 percent for energy-related carbon emissions with material extraction, processing, and discharge leading to the highest environmental impacts in the industry.[26] Cement-based concrete accounts for a total of 8 percent of global carbon emissions alone, with more than 33 billion tons produced yearly worldwide.[27] Another study from Transparency Market Research in 2022 expects the global construction and demolition waste to reach approximately 2.2 billion tons by 2025, doubling the value from the 2012 study.[28] In United States alone, reports from the Environmental Protection Agency shows the 600 million tons of construction waste generated in 2018. Although structural materials such as wood, steel, copper, and brass are valuable commodities for recycling and reuse, present-day architectural assemblies often interface these materials with expanded foams, plastics, and resins, creating irreversible, unrecyclable composites.[29] The construction industry is in dire need to undertake considerable changes in today's linear cycle. The

Fig. 1.8. The circularity in the construction cycle that uses biomaterials as compared to the conventional approach.



30. Livne et al., "Fungal Mycelium Bio-Composite Acts as a CO2-Sink Building Material with Low Embodied Energy." 1

31. AImpani-Lekka et al., "A Review on Architecture with Fungal Biomaterials." 1

32. Dessi-Olive, "Strategies for Growing Large-Scale Mycelium Structures." 2

33. Karana et al., "When the Material Grows: A Case Study on Designing (with) Mycelium-Based Materials." 1

34. Ibid. 3

building sector should minimize the consumption of non-renewable building resources to achieve sustainable practices and a circular economy. This action should be prioritized since the energy demand and carbon footprint from the construction industry are expected to rise because of the rapid growth in population and the development of urbanization processes in developing countries.[30]

A holistic solution to reduce the number of carbon emissions and energy usage in architecture and construction industry is shifting towards the research and development of innovative, renewable construction materials that follow the principles of a circular economy.[31] Although challenging, adopting new ecological materials into the standards of contemporary and future architecture is necessary at a time where buildings are expected to have non-permanent lifespans that commonly ends up in landfill disposals. Evident in most recent works, there is a huge gap between the scale of current construction methods and more experimental materials such as mycelium, bioplastics and other biomaterials. Innovations in materials are required to challenge today's perceptions of significance and building permanence to rethink material consumption and raise awareness of where materials go at their end-of-life.[32] Initiated in the past few decades by multidisciplinary researchers is the use of bio-based materials in design practice which radically changes the passive recipient role of designers to a more active maker of materials. Figure 1.8 presents the significance of bio-based materials as a viable solution to close off the current linear approach in construction.

Often referred to as "Growing Design" by designers during its early stages, the approach refers to producing materials from living organisms to achieve unique biological functions, expressions, and solutions for sustainable design. The approach originated from the advancements in bioresearch initially intended for biological organs and skins for medical purposes. The introduction of biomaterials enable co-creation with nature, reimagining design paradigms for a more sustainable, cross-disciplinary approach that integrates biology with art, architecture, and design.[33] Nevertheless, providing new methods of meaningful product application concepts is not straightforward, it requires a critical understanding of what the material offers in terms of their function and utility. It is important to truly grasp how it gratifies or disturbs people's senses, and what emotions it evokes.[34]

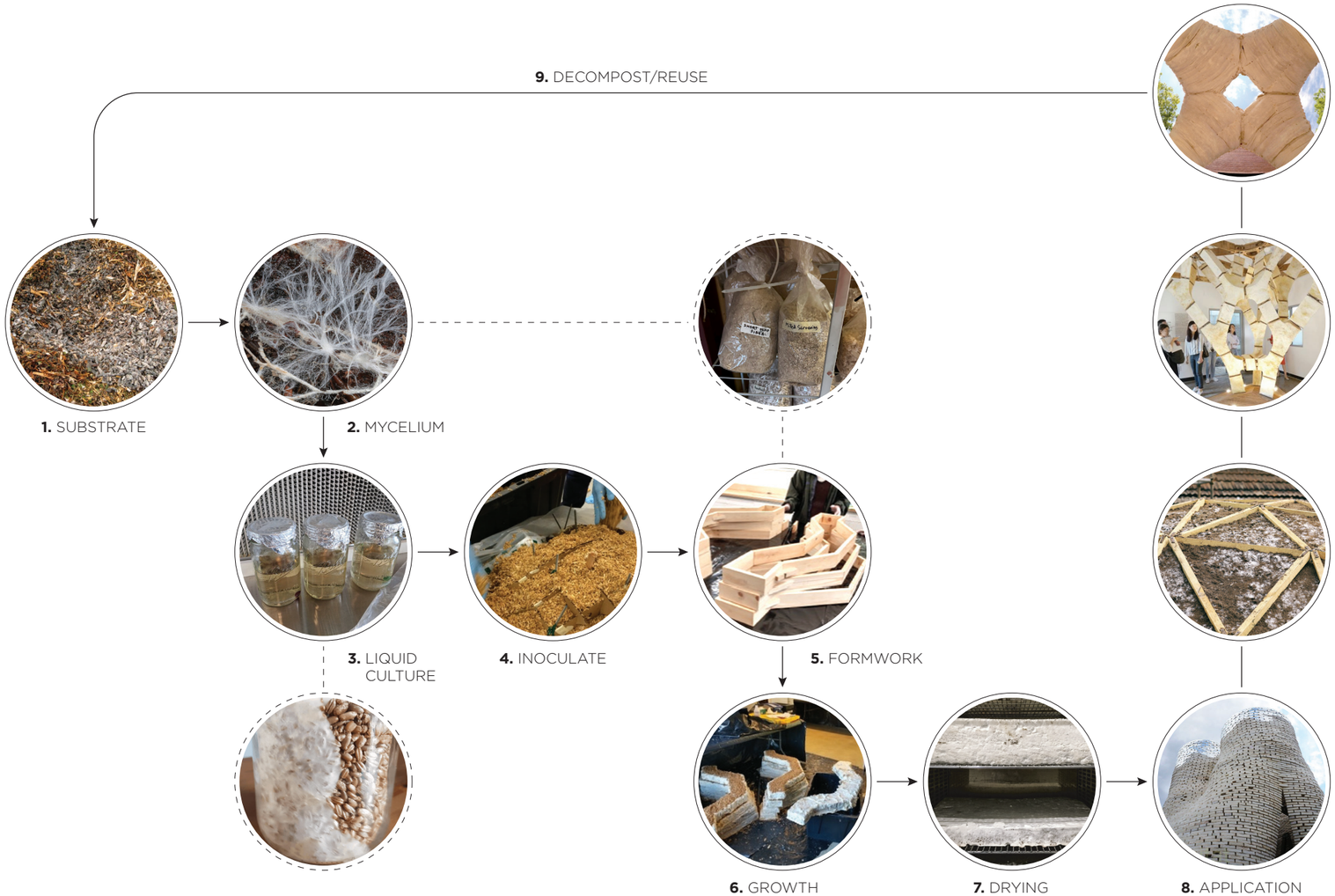
1.2 Mycelium-Based Composites

A Primer

Particularly in the last ten years, there has been great interest in harnessing the properties of mycelium and understanding its different characteristics to develop application techniques for fungal architecture. The interdisciplinary research in this field extracts information about the organism's mechanical properties and aesthetic qualities. The thorough understanding of its physical properties combined with the morphological and philosophical investigations of mycelium pave the ground for designers and architects to visualize a potential alternative future towards a sustainable built environment.[35] Figure 1.9 provides a graphic explanation of "non living" mycelium-based composite's growth process from inoculation to the application of today's mycelial architecture, as well as the additional processes involved including cultivation and mycelium extraction.

35. Almpani-Lekka et al., "A Review on Architecture with Fungal Biomaterials." 2

Fig. 1.9. A typical step-by-step manufacturing process of "non living" mycelium-based projects.



In today's cultivated architecture, mycelium-based composites are often grown by two methods: either by exploiting its biological capabilities to interlock organic substances within its network to produce a bulk material, or through harvesting the liquid culture of mycelium. In terms of bulk mycelium-based materials, the mycelial structure can self-replicate in the presence of appropriate substrates to generate seemingly limitless composites with varying forms and properties.[36] Mycelium-based composites are commonly fabricated by inoculating natural organic substrates with fungal strains, either from the grain fungal spawns or liquid culture extracted from mycelium source. The widely used fungal strains found in literature reviews are *Pleurotus Ostreatus* and *Ganoderma Lucidum*.[37] The substrate of choice should provide necessary nutrients such as carbon, nitrogen, minerals, and vitamins, together with the appropriate amount of water, to achieve mycelium growth.[38] The varying mixtures of substrates described in literature review usually consists of agricultural crop waste such as hemp, wheat, cotton, kenaf, and flax residues. Most experiments use softwood and annual plants, while the smaller majority use hardwood-based substrates combined with carbohydrates as a nutritional supplement.

The inoculation process requires proper sterilization of the substrate mixture to prevent contamination of other harmful organisms through autoclaving, pasteurization, or treatment with chemical agents.[39] Once inoculated, the mixture of mycelium spawn and organic substrates are applied into a pre-shaped mold for incubation. The vegetative mycelium colonizes the organic substrate by branching new hyphae as it feeds through the biodegradable base and interlocking them to form a denser network (see figure 1.10).[40] If a nutritional source is available, mycelium uses the exploitative growing strategy called phalanx to slowly progress in a continuous line, resulting in a thick hyphal mat of fine branches.[41] During incubation, the mixture should be maintained at controlled environmental conditions of light, temperature, and moisture to ensure an uncompromised growth within two to three weeks. Studies show that 25 to 35 degrees Celsius and 65 percent humidity are the best conditions for growing mycelium-based composites. It is also preferable to leave the mixture in dark conditions to prevent fruiting bodies and favor the rapid growth of mycelium networks.[42] After weeks of mycelium colonization, the living organism is eliminated by actively drying the composite. The most common finishing method documented in publications is through oven-drying, while other methods include heat-pressing at the end of the incubation stage.[43]

36. Mohseni et al., "Three-Dimensional Printing of Living Mycelium-Based Composites." 3

37. Digafe Alemu, Mesfin Tafesse, and Ajoy Kanti Mondal, "Mycelium-Based Composite: The Future Sustainable Biomaterial," International Journal of Biomaterials 2022 (March 12, 2022): 4, https://doi.org/10.1155/2022/8401528.

38. Karana et al., "When the Material Grows: A Case Study on Designing (with) Mycelium-Based Materials." 3

39. Elsacker et al., "A Comprehensive Framework for the Production of Mycelium-Based Lignocellulosic Composites." 6

40. Attias et al., "Mycelium Bio-Composites in Industrial Design and Architecture." 3

41. Mohseni et al., "Three-Dimensional Printing of Living Mycelium-Based Composites." 3

42. Karana et al., "When the Material Grows: A Case Study on Designing (with) Mycelium-Based Materials." 4

43. Attias et al., "Mycelium Bio-Composites in Industrial Design and Architecture." 3



Fig. 1.10 A zoomed in photograph of mycelium's hphal bonding of loose organic substrate.

Once fully grown and actively dried for growth stoppage, the mixture results in a three-dimensional live composite mesh of interconnected organic components and fungal fibres. The mycelium-based composites tend to be dense but lightweight weighing in at 0.05 g/cm3, giving them advantageous strength-to-weight ratios over concrete suitable for large-scale material placement and long-span structures. The distinctive characteristics offered by these composites include reduced thermal conductivity than that of other biomasses for insulation, efficient thermal insulation, favourable mechanical properties averaging 1 MPa compressive strength and 0.18 MPa tensile strength, as well as acoustic insulation with 70-75 percent absorbance at 1500 hertz and above.[44] The composite's low thermal conductivity and high specific heat capacity are comparable to conventional insulating materials in current construction. Due to mycelium's high porosity and slight rigidity, the composites are often categorized as insulation foams at the early stage of research development.[45] Compressed mycelium panels are another form of mycelium-based composite end products that have yet to reach the market but are thoroughly researched in some literature. These products are fabricated by either cold or hot-pressing grown mycelium composites. Compressed composites offer compressive strength comparable to timber products such as Oriented Stand Board or medium-dense fibreboards.[46] Moreover, the low manufacturing cost of mycelium-based composite places them as competitive alternatives to conventional construction materials and other bio-based composites. The development of mycelium-based products presents a promising future for ecological construction and architecture.[47]

44. Livne et al., "Fungal Mycelium Bio-Composite Acts as a CO2-Sink Building Material with Low Embodied Energy." 1

45. Xijin Zhang et al., "Naturally Grown Mycelium-Composite as Sustainable Building Insulation Materials," Journal of Cleaner Production 342 (March 15, 2022): 2, https://doi.org/10.1016/j.jclepro.2022.130784.

46. Bitting et al., "Challenges and Opportunities in Scaling up Architectural Applications of Mycelium-Based Materials with Digital Fabrication." 14

47. Ibid. 14

Chapter 2: Growing Matter: Design Shift Towards the Living



2.1 Design Integration of Mycelium-Based Composites

Despite the numerous benefits offered by mycelium-based composites, the products struggle to find their footing in conventional construction applications. Several factors appear to limit the current usage of mycelium-based composites, primarily stemming from low structural strength, high water absorption, and gaps in material property documentation.[48] However, researchers and designers, in turn, remain hopeful in eliminating the drawbacks presented by mycelium-based composites. These limitations allow researchers to come up with solutions to develop the materials necessary for targeted usage in specific applications.[49]

What initially started as eco-friendly alternatives to traditional plastics as biodegradable packaging, mycelium has evolved due to its versatile properties and has been integrated into design and architecture in ways such as wood and concrete alternative, structural support, and temporary structures. A literature review of forty-seven peer-reviewed papers between 2012 and 2019 found multiple application methods of mycelium-based composites affiliated with architecture and design. The study suggests that the composites were used as packaging, acoustic and insulating elements, furniture, cladding and structural support.[50] Illustrated in Figure 2.1, integration of mycelium in today's linear construction cycle could be the vital driver in achieving a sustainable, circular construction cycle.

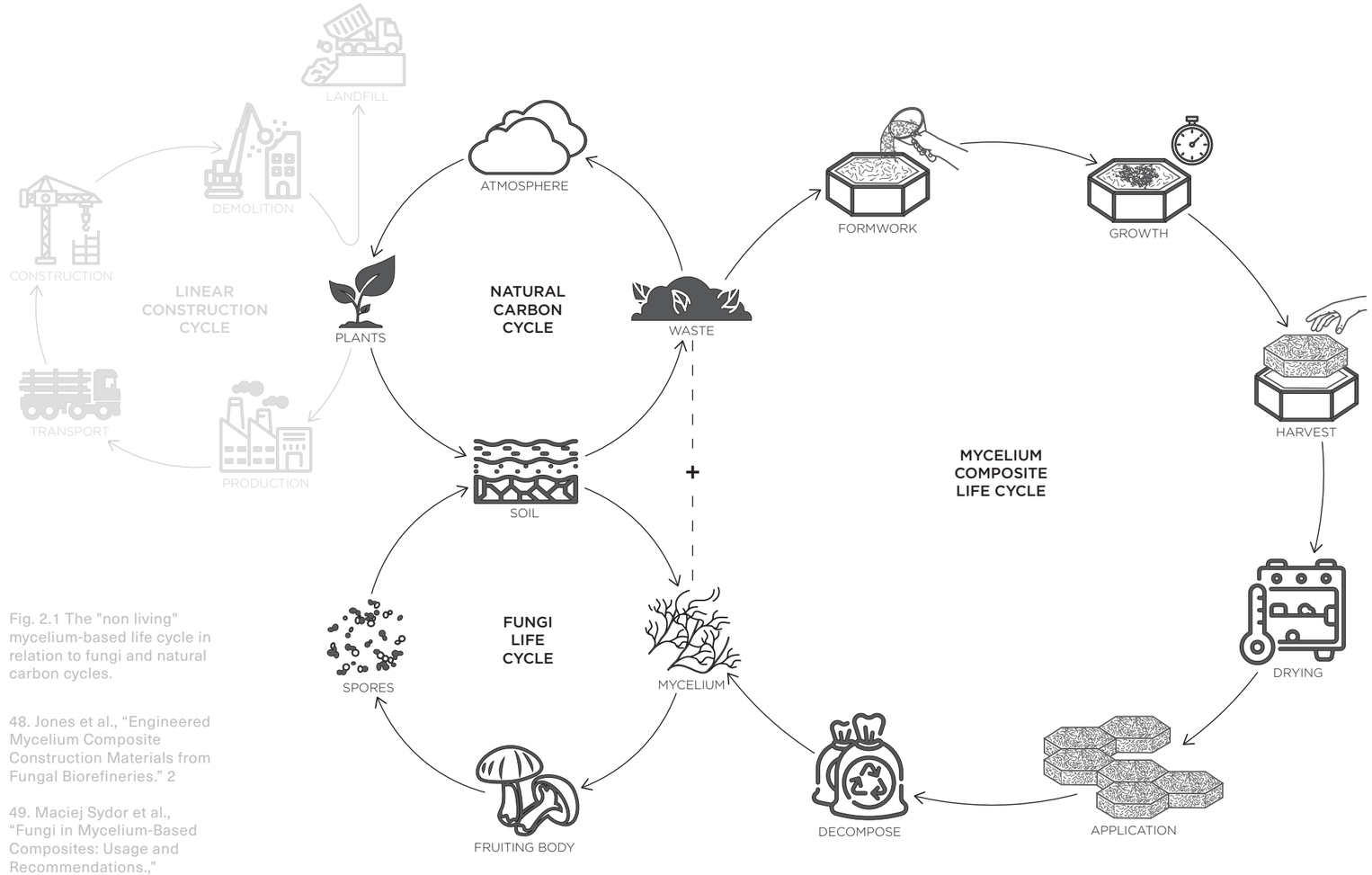


Fig. 2.1 The "non living" mycelium-based life cycle in relation to fungi and natural carbon cycles.

48. Jones et al., "Engineered Mycelium Composite Construction Materials from Fungal Biorefineries." 2

49. Maciej Sydor et al., "Fungi in Mycelium-Based Composites: Usage and Recommendations.," Materials 15, no. 18 (September 1, 2022): 1, https://doi.org/10.3390/ma15186283.

50. Attias et al., "Mycelium Bio-Composites in Industrial Design and Architecture." 15-16

Regarding mycelium-based architectural structures, the initial documented projects were mycelial bricks cast in rectangular-shaped plastic molds, stacked in a brick-and-mortar manner.[51] The commonly applied method of mycelium-based bricks was seen in structurally applied projects such as Mycotecture Alpha, shown earlier in figure 1.5, a small-scale catenary vault made entirely out of mycelium bricks grown from Reishi. The early projects of mycelium architecture assumed that the materials would only work in compression applications, thus, experimentations with domes, vaults, towers, and columns dominated the early literature of the field.[52]

Mycelium-based composites are often praised for their early stacked brickwork. However, figure 2.2 shows an emerging method of in-situ monolithic casting also started gaining interest from designers in the industry. Though considered much weaker than brick and panel products, grow-in-place monolithic structures inherit many advantages of cast-in-place concrete techniques focused on stereotomic approaches and mainly the use of formwork to produce upscaled mycelium composites.[53] Due to the challenges of cultivating large volumes of live mycelium because of high contamination risks, and constructing of wasteful formworks to facilitate growth, the monolithic approach found lesser projects in the context of architecture and design.[54] Incorporating mycelium into architecture and construction is not an easy task and requires interdisciplinary collaboration, continuous experimentation, and true commitment to sustainability. As the specialized field continues to evolve, there will likely be an increase in innovative applications for mycelium in the built environment to promote a circular economy.

51. Ibid. 2

52. Dessi-Olive, “Strategies for Growing Large-Scale Mycelium Structures.” 3

53. Biala and Ostermann, “Mycostructures—Growth-Driven Fabrication Processes for Architectural Elements from Mycelium Composites.” 4

54. Dessi-Olive, “Strategies for Growing Large-Scale Mycelium Structures.” 4



Fig. 2.2. The formwork required for in-situ monolithic casting of mycelium-based structure.

2.2 Literature Review

The First Generation of Mycelial Architecture

While still lacking comprehensive understanding, the experimental design movement of mycelial architecture, defined by the exploration of various forms and applications, embodies a collective curiosity among designers. In recent years, few projects and installations have shown an underlying appreciation for fungi as exceptional biological components and valuable contributors to the design process. One of the leading researchers of mycelium, Elise Elsacker, claims that the previous studies of mycelium architecture show almost no consideration towards the assessment of norms, which is essential for the implementation of the materials for large-scale, conventional applications. She believes that older literature and shared knowledge regarding mycelium are very fragmented, lacking consistency and a standardized overview of the production parameters and properties.[55] As an effort to achieve consistency in reviewing projects from published literature, the analysis of multiple projects in the context of mycelium-based architecture will follow a set of parameters shown in Table 1, laying out the varying elements that influence each project. The following section examines various projects of mycelium-based construction and design published in the literature review to understand the potential and challenges of contemporary mycelial architecture.

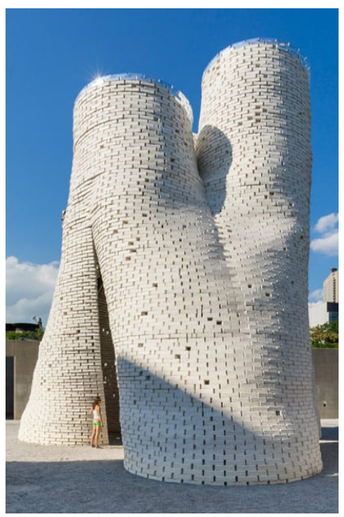
55. Elsacker et al., "A Comprehensive Framework for the Production of Mycelium-Based Lignocellulosic Composites." 2

PARAMETRES	DEFINITIONS
Fungal Species	The specific strand of fungi used to grow Mycelium that influences the properties of Mycelium on varying substrates. Specific strands produce fluffier Mycelium suitable for insulation purposes while others produce denser root fibers for higher structural properties.
Substrate Mixture	The type of organic materials used as a base for the growth of Mycelium. Substrates are usually bounded by the hyphae of fungi to provide hardening characteristics to Mycelium-based materials. The organic waste used often provides nutrients for the fungi to grow.
Site	The location of where the project or installation took place. Locating the project is important when considering availability of organic waste, environmental conditions, and availability of resources and labs.
Climate	The weather conditions of where the projects are located. Climate plays a vital role in determining the factors of growing Mycelium based on the site's humidity, precipitation, and temperature. Mycelium's current growth requirements rely heavily on controlled temperature
Packing Method	The technique used to allow Mycelium to colonize the substrate. Most common method in the industry is packing into shaped molds while monolithic approaches are slowly gaining more attention.
Incubation Period	The number of days it takes for Mycelium colonization. Different fungi strains require different periods to fully colonize a substrate, so incubation is important to consider depending on the project timeline.
Drying Method	The method of killing the Mycelium to stop its growth. Drying fully colonized substrate not only prevents mushroom fruiting but also hardens the product to increase its strength.
Formwork	The type of structural support in which the inoculated substrate is placed. Different types of formworks are used depending on the architectural applications of the project.
Application	The method of using Mycelium-based materials. It initially started by using myco-materials as packaging but was advanced and is currently being used architecturally as insulation, envelope, and structural support.
Architectural Method	The varying approaches to achieve architecturally viable projects. Most commonly known to be used as blocks and panels that follow the brick-and-mortar approach but are slowly emerging into monolithic casting and bio-material assemblies.

Table 1. Set of parametres that influence the viability of mycelium-based works.

PARAMETRES	DEFINITIONS
Post Treatment	The treatment that each Mycelium-based materials undergo once the substrate is colonized. Drying is typically the method to inactivate the fungi, but other approaches also produce different varieties aside from bricks.
Fungal Spawn Type	The form of the Mycelium source used to inoculate substrate. There are 2 types of spawns, grain spawn and liquid culture. Liquid culture is more common in living Mycelium projects as it can be mixed easily with different types of surfaces and directed-growth formworks.
Inoculation Method	It is the process of mixing the fungal strain within the base or substrate in which the Mycelium is expected to grow. Initially, the method was to always mix the strain with the substrate, but the living-growth approach introduced 3D inoculation and injection.
Growth Process	The process of growing Mycelium. The non-living projects typically grow Mycelium in molds but the shift to living Mycelium saw processes such as growth-directed fiber, binding growth, and more.
Growth Conditions	The condition of where Mycelium is allowed to grow. The selected projects display different types of growing conditions from indoor, controlled, sanitized, to outdoor, exposed, and uncontrolled. Light exposure is also another critical factor to avoid fruiting to occur.
Composite Exposure	The exposure of the growing or unalive Mycelium composites. The main difference between non and living growth is that the living Mycelium composites are more prone and exposed to contamination due to not being fully enclosed to study the organic growth of fungi.
Containment	The type of enclosure (if contained) used to let the biological living growth process occur. Containing living Mycelium can be as simple as covering it with plastic while some methods include usage of incubators and organic formwork.
Sterilization Method	The killing of microorganisms to avoid contamination. Some common practices are sterilization of the substrate through pressure cooking, sanitization of growing environment, and containment of the composite.
Formwork Components	The materials used to support the living growth process of Mycelium in comparison to only providing structural support for the non-living Mycelium composites. Most of the living Mycelium projects use some sort of fiber-like material to direct the growth of Mycelium.
Hardware & Software	The advancement of hardware and software to assist the living growth of Mycelium. In comparison to the oven used in the non-living approach, the use of 3D printers, and digital modelling are slowly becoming integrated with the growing of Mycelium-based materials.

One of the pioneering and more known fungal-based projects that engage construction at the material, manufacturing, and waste stages of a building's life cycle is the *Hy-Fi* Tower (see figure 2.3).[56] Standing at 12 metres high, Hy-Fi is an organic compostable mycelium-based structure designed by David Benjamin and The Living and engineered by firm Arup in 2014.[57] Shown in figure 2.4, the installation consists of approximately 10,000 mycelium-based bricks was showcased by the New York Museum of Modern Art at the MoMA PS1 exhibition, and is the largest and perhaps the most widely publicized mycelium structure.[58] At the core of the project's material stage, local waste of corn stalks was chosen as the composite's substrate and was packed into impermeable polypropylene moulds.[59] After mycelium colonization during its incubation phase, the bricks were oven-dried, producing strong, but inert bricks. The MCB bricks sourced by Ecovative were stacked using traditional mortar and supplemented with structural timber structure as support with a few internal metals for additional shear force connection.[60]After three months, all MCB bricks were composted and distributed to local gardens as agricultural feedstock.[61]



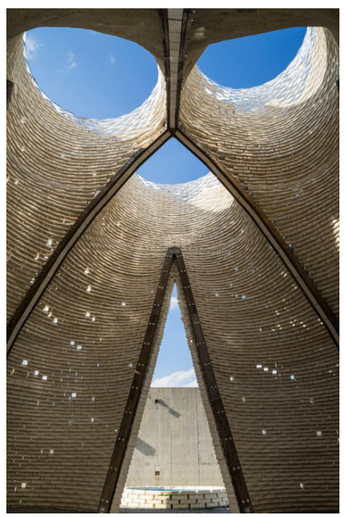


Fig. 2.3 (left). The exterior view of the *Hy-Fi* by David Benjamin and The Living at the MoMA PS1 exhibition.

Fig. 2.4 (right). An interior photograph showing the framework that supports 10,000 mycelium-based bricks.

56. Campbell et al., "Modular Mycelia." 4

57. Dessi-Olive, "Strategies for Growing Large-Scale Mycelium Structures." 3

58. Jones et al., "Engineered Mycelium Composite Construction Materials from Fungal Biorefineries." 4

59. Biala and Ostermann, "Mycostructures—Growth-Driven Fabrication Processes for Architectural Elements from Mycelium Composites." 2

60. Attias et al., "Mycelium Bio-Composites in Industrial Design and Architecture." 2

61. Almpani-Lekka et al., "A Review on Architecture with Fungal Biomaterials." 4

62. Dessi-Olive, "Strategies for Growing Large-Scale Mycelium Structures." 5

63. Leschok and Dillenburger, "3D Printed Formwork for Mycelium Bound Composites." 4

64. Biala and Ostermann, "Mycostructures—Growth-Driven Fabrication Processes for Architectural Elements from Mycelium Composites." 3

65. Bitting et al., "Challenges and Opportunities in Scaling up Architectural Applications of Mycelium-Based Materials with Digital Fabrication." 13

66. Dessi-Olive, "Strategies for Growing Large-Scale Mycelium Structures." 5

Monolito Micelio, also known as *Monolithic Mycelium*, represents an experimental utilization of mycelium as a primary building material practicing the method of in-situ casting. The monolithic structure shown in figure 2.5, is the third prototype designed by a group of graduate research students at the Georgia Tech School of Architecture, led by Assistant Professor Jonathan Dessi-Olive.[62] Grown in early 2018, the structure is a large-scale 2.5 metric cube pavilion made from one-ton colony of mycelium-stabilized hemp provided by Ecovative.[63] The arch structure was only given under five days to grow and let mycelium colonize its substrate. The shaped interior formwork which originated from splitting funicular columns and assembling them into a symmetrical, four-legged vault shell inscribed in a cube was later lost after mycelium concealment (see figure 2.6).[64] The nylon geotextile used as external formwork and protection from contamination was removed days later to allow the arch to air dry for several weeks.[65] The experiment was prompted to the observe the monotony of brick/block-based myco-fabrication methods. The pavilion successfully demonstrated that mycelium-based materials could inherit fabrication logics from convention practices such as cast-in-place concrete, board formwork, and flexible formwork techniques.[66] Questions may still exist about long-term durability and performance of mycelium-based projects in the construction industry, yet the vault demonstrated the importance of geometry and the possibility of growing mycelium-based structures in-situ in an unsterile environment.





Fig. 2.5 (left). A photograph of *Monolito Micelio* by Jonathan Dessi-Olive.

Fig. 2.6 (right). Students from Georgia Institute of Technology setting up the formwork for in-situ casting of the prototype.



Fig. 2.7. An exterior view of *Growing Pavilion* at the Dutch Design Week 2019.

Designed as a cylindrical space to shelter communal events, artist and designer Pascal Leboucq, in collaboration with Erik Klarenbeek's Known Design Studio, designed the *Growing Pavilion* for the Dutch Design Week 2019 event. The pavilion showcases biodegradable materials that consist of mycelium, wood, hemp, cattail, and cotton.[67] Shown in figure 2.7, the main feature of the structure is the organically formed mycelium-based panels that make up its façade. The panels are produced with a mixture of hemp and aspen wood, inoculated with the fungal strain of *Ganoderma*. The substrate was sourced locally from the residual flows of local farmers in the Netherland.[68] The panels, manufactured by Ecovative, were mounted directly to the supporting formwork of timber frame loadbearing structures and displays the non-structural implementation of mycelium-based composites as façade cladding, exhibiting their sculptural faces that contribute to the pavilion's aesthetic appeal.[69] Other biomaterials were also used in combination with the mycelium-based composites to serve as a platform for demonstrating the capabilities of bio-based components.[70] The interior space implemented draping made entirely out of organic cotton and the flooring material was made out of bio-laminate. During its time at the exhibition, musical performances were held inside to promote mycelium sound absorption capabilities to visitors before the structure was taken down and recycled locally.[71]

67. Bitting et al., "Challenges and Opportunities in Scaling up Architectural Applications of Mycelium-Based Materials with Digital Fabrication." 14

68. Ibid. 14

69. Biala and Ostermann, "Mycostructures—Growth-Driven Fabrication Processes for Architectural Elements from Mycelium Composites." 3

70. Leschok and Dillenburger, "3D Printed Formwork for Mycelium Bound Composites." 4

71. Almpani-Lekka et al., "A Review on Architecture with Fungal Biomaterials." 5-7

72. Bitting et al., "Challenges and Opportunities in Scaling up Architectural Applications of Mycelium-Based Materials with Digital Fabrication." 13

73. Sebahat Sevde Sağlam and Seden Acun Özgünler, "An Experimental Study on Production Opportunities of Biocomposite by Using Fungal Mycelium," Journal of Design for Resilience in Architecture and Planning 3, no. 2 (August 31, 2022): 10, https://doi.org/10.47818/DRArch.2022.v3i2056.

74. Almpani-Lekka et al., "A Review on Architecture with Fungal Biomaterials." 4

75. Bitting et al., "Challenges and Opportunities in Scaling up Architectural Applications of Mycelium-Based Materials with Digital Fabrication." 13

76. Sağlam and Özgünler, "An Experimental Study on Production Opportunities of Biocomposite by Using Fungal Mycelium." 10

The *Shell Mycelium Pavilion* is a collaborative mycelial project between BEETLES 3.3 and Yassin Areddia Designs in India, as an innovative testament to the development of mycelium-based architecture and design.[72] As seen in figure 2.8, the project combined the prefabricated modules of mycelium-based panels as well as the in-situ casting for assembly and growth of mycelium in an open and non-sterile environment.[73] The structure utilizes a triangular timer framework as its main structural geometry with steel connectors to form a wooden grid shell structure.[74] The cavities within the timber structure grid shown in figure 2.9, were filled with mycelium-inoculated substrates of coconut husk fibers and woodchips. Over time, the inoculated mixture dries, killing the organism and forming a protective shell overpowering the main framework of the timber structure.[75] A notable aspect of the project is its aim to explore the potential of mycelium-based construction to create a lightweight and dismantlable structure suitable for temporary events. In addition, the project promotes the possibility of mycelium to flourish on-site, in an exposed environment, and naturally drying the components through sunlight exposure.[76]





Fig. 2.8 (top). A photograph of *Shell Mycelium* in India.

Fig. 2.9 (bottom). A zoomed in photograph of mycelium growing on gaps filled with inoculated substrate.

A joint effort between Karlsruhe Institute of Technology, Swiss Federal Institute of Technology Zurich, Future Cities Laboratory Singapore, and Mycotech, *MycoTree* represents a pioneering work that explores the potential of mycelium-based composites as a load-bearing structure.[77] *MycoTree* is a self-supporting structure exhibited at the Seoul Biennale for Architecture and Urbanism as part of the interior projects. The project utilizes mycelium composites in conjunction with parametric design and digital manufacturing to create an innovative mycelium structural design.[78] The design stems from the implementation of 3D Graphic Statics, a structural form-finding method that generates compression-only funicular structures.[79] The *MycoTree*, shown in figure 2.10, structural column stands at three-metre-high supported by MBC blocks, tensioned by a 4m x 4m bamboo grid system that acts as its tensioning elements. Additional bamboo composite plates connected with dowels provided increased reinforcement to the blocks, showcasing a technique that integrates both organic and conventional materials in structural design.[80] The new approach of the project underscores the structural capacity of mycelium when placed in compression-only configurations taking inspiration from the early dominating works of domes, towers, and vaults of mycelium projects.[81]

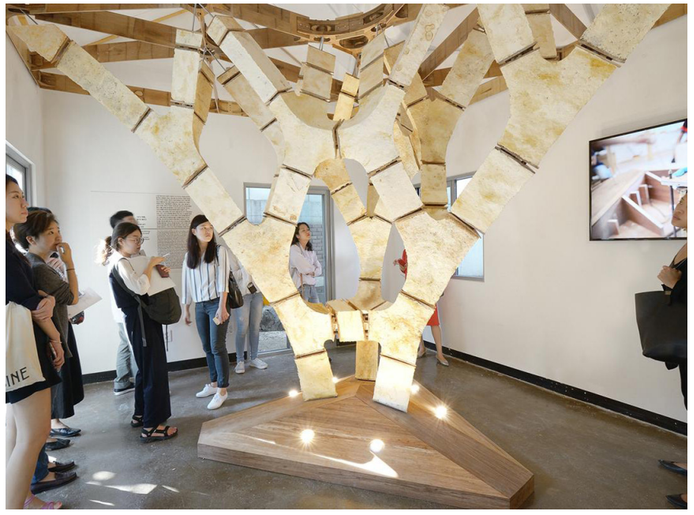


Fig. 2.10 An image of *MycoTree* exhibited at the Seoul Biennale for Architecure and Urbanism.

77. Bitting et al., "Challenges and Opportunities in Scaling up Architectural Applications of Mycelium-Based Materials with Digital Fabrication." 14

78. Almpani-Lekka et al., "A Review on Architecture with Fungal Biomaterials." 4

79. Bitting et al., "Challenges and Opportunities in Scaling up Architectural Applications of Mycelium-Based Materials with Digital Fabrication." 14

80. Biala and Ostermann, "Mycostructures—Growth-Driven Fabrication Processes for Architectural Elements from Mycelium Composites." 3

81. Dessi-Olive, "Strategies for Growing Large-Scale Mycelium Structures." 3

82. Campbell et al., "Modular Mycelia." 4

83. Dessi-Olive, "Strategies for Growing Large-Scale Mycelium Structures." 5

84. Almpani-Lekka et al., "A Review on Architecture with Fungal Biomaterials." 4

85. Mohseni et al., "Three-Dimensional Printing of Living Mycelium-Based Composites." 3

86. Campbell et al., "Modular Mycelia." 2

The advancement of mycelium-based composites in the construction industry is quite evident from the projects discussed above. Despite the promising benefits provided by the constant evolution of mycelium-based architecture and design, various projects remain to encounter challenges that underscore the lack of diversity in current building approaches (see figure 2.11). The *Hy-Fi Tower*, for example, is undeniably architecturally viable but lacks biological utility in its design process. The role of fungi in the project was confined to mainly brick production rather than being the driver of the structure's form and assembly method. The project expressed an existing method of conventional construction that lacked utilization of mycelium's specific biological processes, later explored in the living category.[82] *Monolito Micelio*, on the other hand, encountered degradation caused by constant precipitation and temperature swings. In addition to the rigidity of its internal reinforcing system, the design team noticed the negative influence of people's curiosity, causing them to tinker with the unfinished structure.[83] Similarly, the *Shell Mycelium Pavilion* faced numerous issues with weather resistance, causing the structure to dry out prematurely, revealing the limitations of mycelium architecture on open-air applications.[84]

In response to the challenges mentioned, the field of mycelium architecture continues to seek innovation and shift towards a more holistic approach. As demonstrated in *Shell Mycelium* and *Growing Pavilion* projects, methods such as digital fabrication or unbounded growth of mycelium-based composites offer promising avenues that could further enhance mycelium's material performance. A novel approach in mycelium architecture that is slowly gaining popularity as per recently published works is the transition to the living mycelium approach.[85] Despite the clear sustainability, cost-effectiveness, and structural benefits offered by conventional mycelium construction approach, the natural property of the material is often neglected. By preserving the living nature of mycelium, an innovative method emerges that embodies sustainable principles greater than the traditional practices of dried mycelium materials. The living approach could potentially lead to adaptable and dynamic structures that evolve and respond to their surroundings, ushering in a symbiotic relationship between the built environment and the natural ecosystems.[86]





Fig. 2.11. Analytic illustrations of some issues faced by the projects mentioned above.

2.3 The Living

Mycelium Alive

As a reflection of section 1.1: Mycelium Marvels: The Living, transitioning to the living mycelium approach represents a departure from the more commonly practiced methods of dried mycelium-based composite construction. Certain individuals including Sean Campbell and Elise Elsacker, have been challenging the industry to push forward the true potential of utilizing the outstanding biological properties of mycelium. They believe that with the advancement of digital tools and technology, the design language of the built environment has become diverse.[87] They claim that despite all the benefits that the projects mentioned above have offered, the true potential of mycelium as a building material alternative lies in its capacity for self-organized, responsive growth. Instead of viewing mycelium as a grow-kill material only, future research in the context of mycelium construction can focus on the unique temporality of the material as a quality, not as a definitive decay, but as a component of regeneration and reintegration in the cycle (see figure 2.12).



Fig. 2.12. Zoomed in photograph of mycelium colonizing its organic substrate.

87. Almpani-Lekka et al., "A Review on Architecture with Fungal Biomaterials." 8

88. "Nature's Mysterious Networks: Mushrooms, Mycelia and Yeasts - GroundWork," April 13, 2021, https://www.groundworkgallery.com/exhibition/natures-mysterious-networks-mushrooms-mycelia-and-yeasts/, https://www.groundworkgallery.com/exhibition/natures-mysterious-networks-mushrooms-mycelia-and-yeasts/.

89. Emily Watlington, "Mushrooms as Metaphors," ARTnews.Com (blog), December 29, 2021, https://www.artnews.com/art-in-america/features/mushrooms-as-metaphors-urbonas-studio-tj-shin-xiaojing-jan-1234614585/.

90. "Nature's Mysterious Networks."

The growing interest in mycelium within the architectural and art communities is not only a reflection of the material's unique structural properties but its deep cultural and theoretical resonance as well. Mycelium exhibits the constant processes of growth and decay, which embodies the concept of living architecture and art in a fascinating manner. Thus, the organism has been the subject of study, as artists and designers seek to translate the unfamiliarity of the material to make people acquainted with the unknown.[88] The interest in fungi isn't merely about exploring the origins of life or networks of the natural world, as might have been in earlier artistic inquiries. Instead, these artists are drawn to fungi because of their symbolism and relevance to current global concerns. Particularly in their ecological role, mushrooms are associated with regeneration and decomposition. By having varying approaches to displaying fungi's cycle of life, artists are using them as a metaphor to address issues such as environmental degradation, climate change, and potential ecosystem collapse.[89] For example, Alexandra Steiner, a painter and biologist, produces a series of paintings of mycelium's iridescent forms and patterns as a way of sharing a deeper knowledge of the habits of mycelia (see figure 2.13). Through these paintings, the "invisible" is visible and accessible to the viewers.[90]

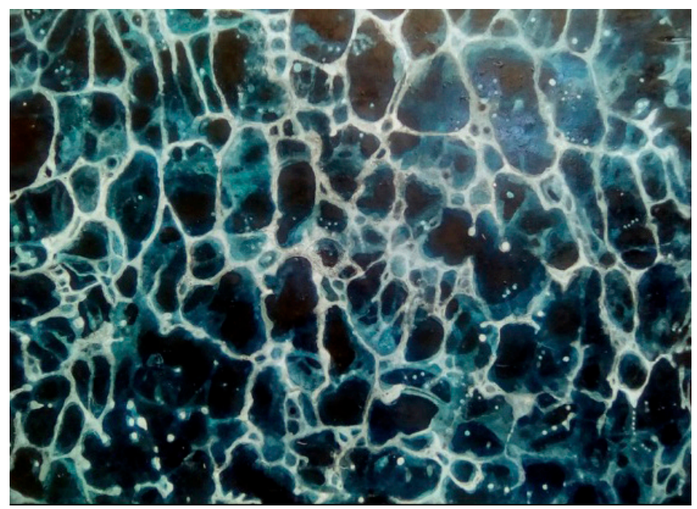


Fig. 2.13. Alexandra Steiner's Mycelium Painting

Another notable project that exemplifies the integration of cultural and ecological principles above is *Mycelium Mockup* by AFJD Studio, an installation made from living mycelium-based bricks that suggests a future where edible buildings can be grown from locally available resources. The project is inspired by soft systems, a concept in which predictable, linear systems with independent parts evolve into nonlinear systems, where complexity comes from the changing relationships between elements. The installation overcomes the biological mould limitations by allowing growth after assembly, not only binding the blocks together but also producing fruiting bodies, later harvested and served to the visitors for a heightened experience of the material (see figure 2.14).[91]

The responses to living mycelium architecture, or living architecture in general can be complex and varied, as a result of curiosity, apprehension, and fascination. Responsive living mycelium architecture as a building material can evoke a sense of connection with nature. The spatial experience offered by mycelium in which the building is alive, capable of growth, and self-healing can be extremely appealing, fostering a sense of well-being and mindfulness in its occupants.

However, there are a few psychological challenges associated with fungi. It is undeniable that many are still accustomed to the stability, predictability, and permanence of traditional non-living building materials such as concrete, steel, and glass. The idea of a building alive, that undergoes constant changes over time, may provoke feelings of uncertainty and discomfort. Particularly for mycelium, concerns about maintenance, durability, and hygiene may arise. The unfamiliarity of living materials as compared to the inert ones may be disorienting, leading some to view them with skepticism.

The perception of living mycelium architecture remains shaped by the balance between excitement about its innovative, environmentally friendly potential and the inherent uncertainties that come with challenging the conventional notions of today's construction and architecture practices.

91. Joseph Dahmen, "Soft Matter: Responsive Architectural Operations," Technoetic Arts: A Journal of Speculative Research 14, no. 1/2 (June 2016): 120, https://doi.org/10.1386/tear.14.1-2.113_1.

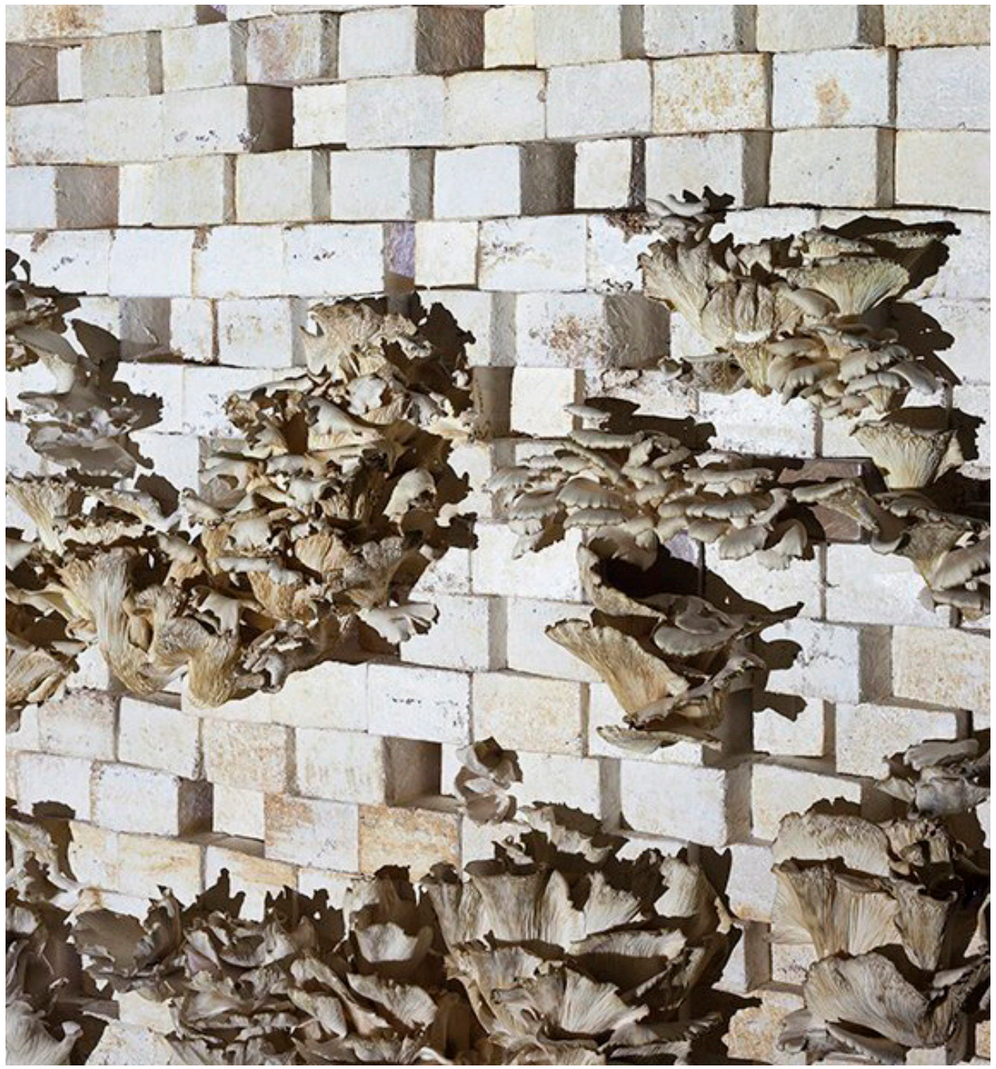


Fig. 2.14. Fruiting bodies present on the edible installation, *Mycelium Mockup,* by AFJD Studio.

Mycelium Alive: Integration

How can living mycelium serve as design rules of the future mycelial architecture? How can the robustness of the complex hyphae networks of mycelium be the influencing drivers of the works in the field?[92] It seems that the manufacturing of volume materials such as mycelium as shaped formwork process restricts the potential of the organism to offer free-forming components.[93] As shown in figure 2.15, the shift to the living approach allows for more efficient and less carbon emitting processes by removing two of the highest contributors of carbon emissions, which are the moulding and drying stages. The growing interest in living materials as design components is motivated by the desire to create sustainable materials without further adding to the environmental waste crisis.[94] The goal of the research towards the shift to the living mycelium approach is not restricted to producing new functional fungal architecture, instead, to demonstrate the strengths of its natural properties and outlining the technical benefits that the living organism may offer as means of architectural assemblies.[95]

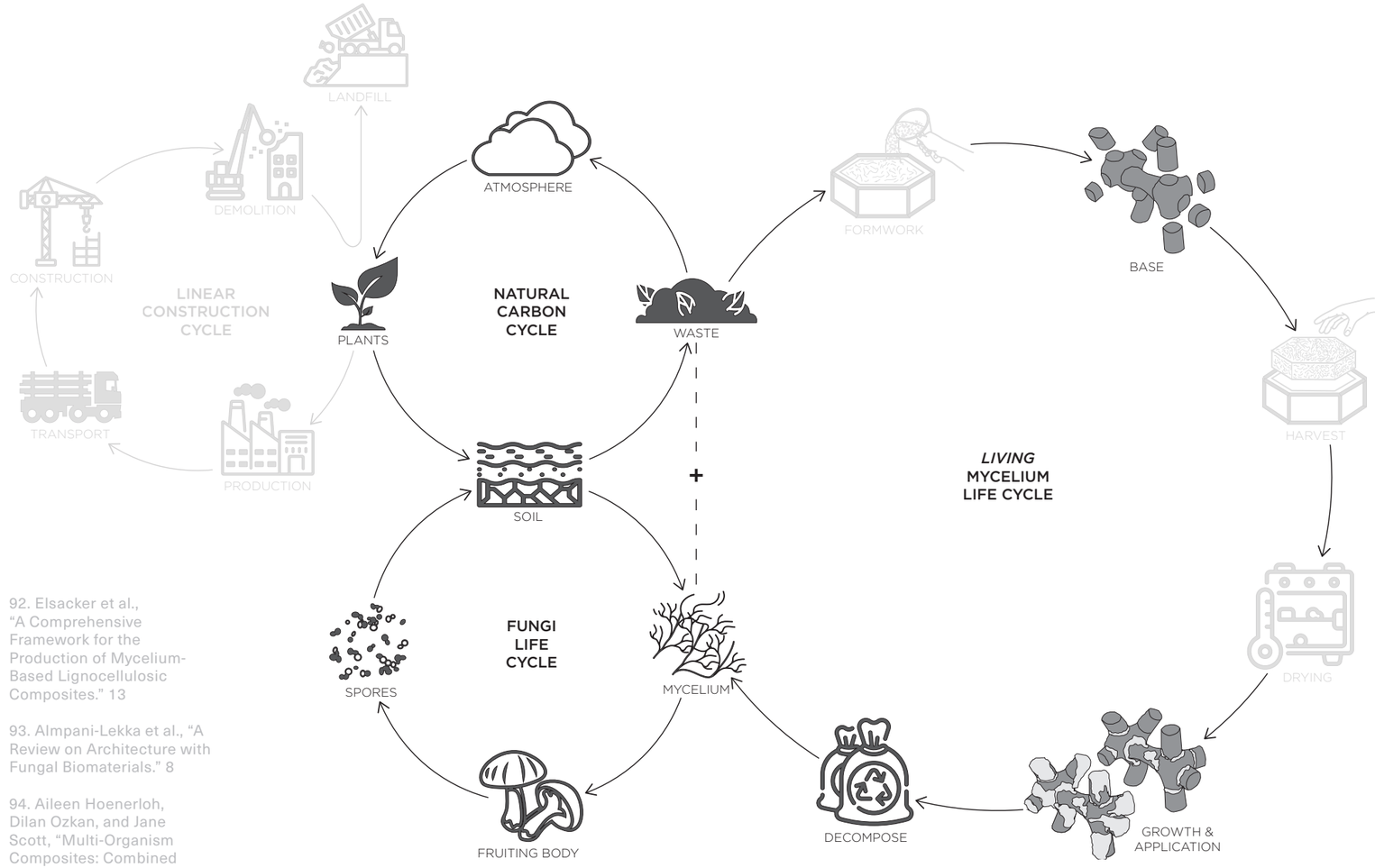


Fig. 2.15. The "living" life cycle in relation to the fungi and natural carbon cycles.

92. Elsacker et al., "A Comprehensive Framework for the Production of Mycelium-Based Lignocellulosic Composites." 13

93. Almpani-Lekka et al., "A Review on Architecture with Fungal Biomaterials." 8

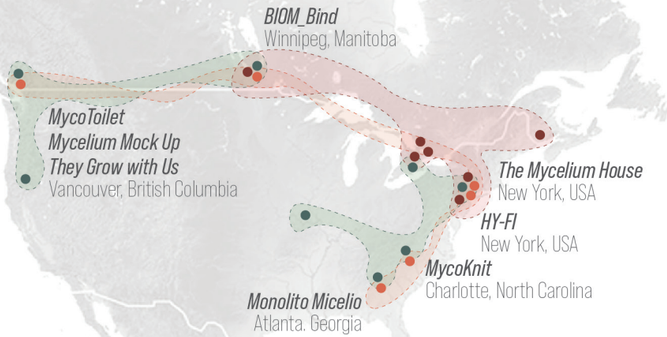
94. Aileen Hoenerloh, Dilan Ozkan, and Jane Scott, "Multi-Organism Composites: Combined Growth Potential of Mycelium and Bacterial Cellulose," Biomimetics (Basel, Switzerland) 7, no. 2 (2022): 1, https://doi.org/10.3390/biomimetics7020055.

95. Campbell et al., "Modular Mycelia." 5

2.4 The Living Design

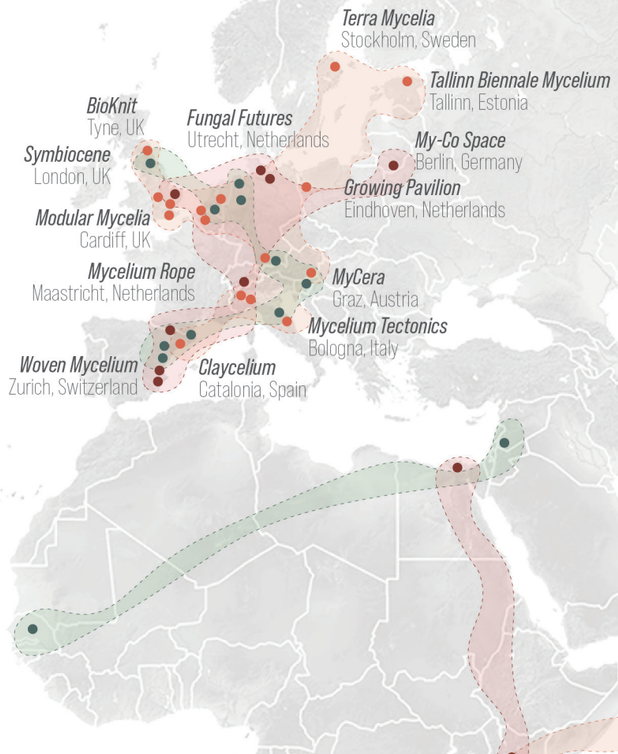
A Generational Shift

To fully understand the industry of mycelium architecture in a global context, a mapping exercise seen in Figure 2.16 on existing mycelial projects, and the groups and individuals involved, including researchers and research groups, organizations, and institutions, was conducted to identify singular and interdisciplinary collaborations.



LEGEND

- **Project**
  - HyFi
  - Claycelium
  - Mycera
  - BioKnit
  - BIOM_Bind
  - Mycelium Rope
  - Mycelium Tectonics
  - Shell Mycelium
  - Monolito Micelio
  - Growing Pavilion
  - MycoTree
  - Modular Mycelia
  - Circular Garden
  - Woven Mycelium
  - Tallinn Biennale Mycelium
  - MycoToilet
  - The Tree Column
  - The Living Column
  - The Mycelium House
  - Symbiocene
  - Hydra
  - Terra Mycelia
  - Knitted Mycelia
  - Mycomerge
  - Fungal Futures
  - My-Co Space
- **Research Lab & Company**
  - Ecovative
  - LeShroomery Inc.
  - Arup
  - Yassin Arredia Design
  - Company New Heroes
  - Mogu
  - AIA New York
  - MIT Media Lab
  - The Living
  - Studio Beetles
  - Block Research Group ETH Zurich
  - Future Cities Laboratory
  - My-Co-X Collective
  - IAAC Barcelona
  - CITA
  - PLP Labs
  - Digital Building Technologies
  - Blast Studio
  - Studio Edward
  - KIT Karlsruhe Germany
  - Mycotech Lab Indonesia
  - Hub for Biotechnology in-
  - the Built Environment
  - Shape Lab
  - BIOM_Lab
- **University**
  - University of Waterloo
  - University of British Columbia
  - University of Manitoba
  - University of Stuttgart
  - University of Oregon
  - University of Bologna
  - Georgia Institute of Technology-
  - School of Architecture
  - Rensselaer Polytechnique Institute
  - Kansas State University
  - Vrije Universiteit Brussel
  - Swinburne University
  - Utrecht University
  - Maastricht University
  - Graz University of Technology
  - Singapore University of Technology and Design
  - MAS dFab ETH Zurich
  - Institute for Advanced Architecture of Catalonia
  - Italian Institute of Technology
  - Newcastle University
  - Jan Van Eyck Academie
  - Karlsruhe Institute of Technology
  - North Carolina State University
  - Cardiff: Welsh School of Architecture



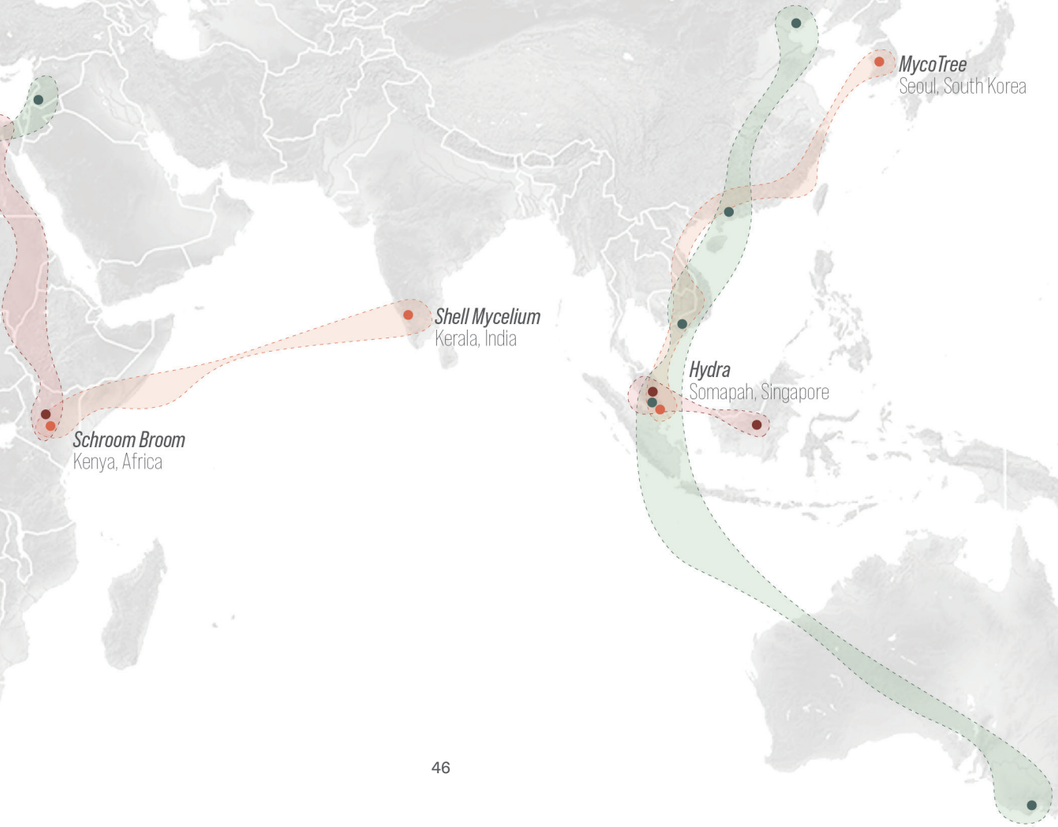


Fig. 2.16. A mapping of published mycelium-based architectural projects and installations.

A significant finding from this exercise is the notable interest in the biological utilization of mycelium composite as a living component in design. As shown in Figure 2.17, it is encouraging to see that more recent projects are clear indications that there is a current design paradigm shift of designers transitioning to experimental works of mycelium to further develop and explore its unseen potential as a living material.

A few of the projects listed in the diagram can be seen to suggest new hybrid techniques of mycelial construction that could contribute to the broader canon of fungal fabrication integrated with today's available tools. Evident in the comparative diagrams provided in Figure 2.18 and 2.19, both the non-living and living approaches provide valuable contributions to the construction industry in their respective ways. The diagrams show a noticeable difference in the amount of time that mycelium is in its living state. Additionally, the non-living projects are often displayed and exhibited after the mycelium has been dried, while the living projects showcase the biological capacities of mycelium during its growing phase.

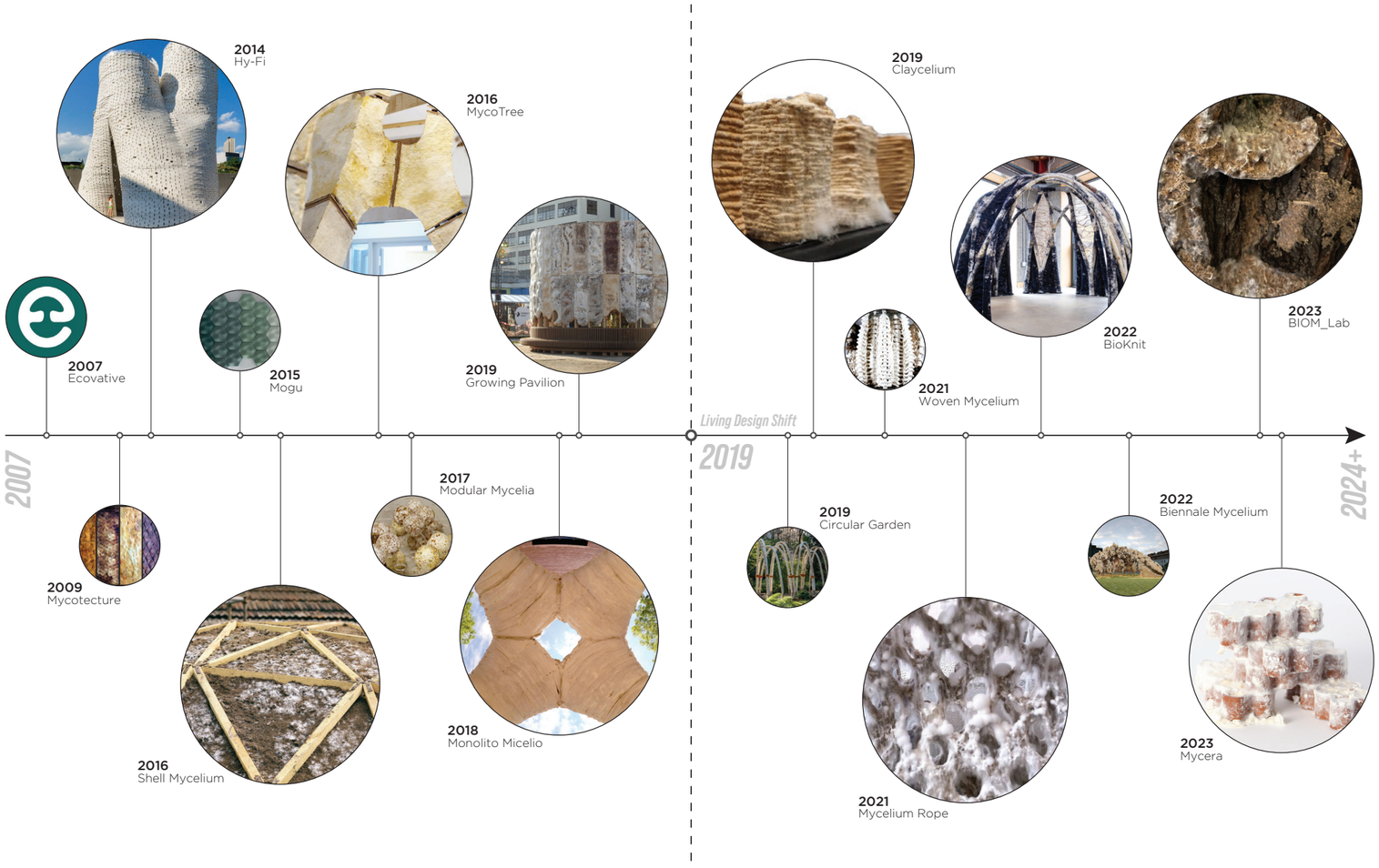
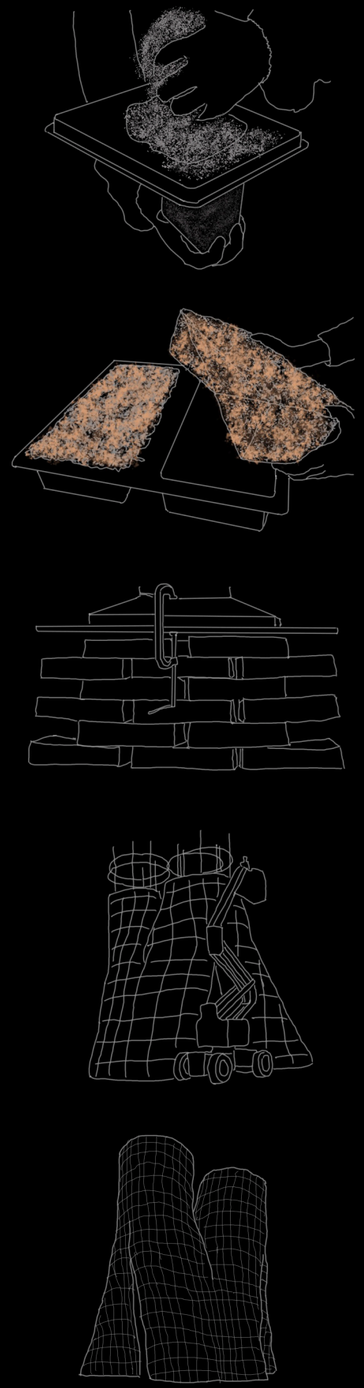
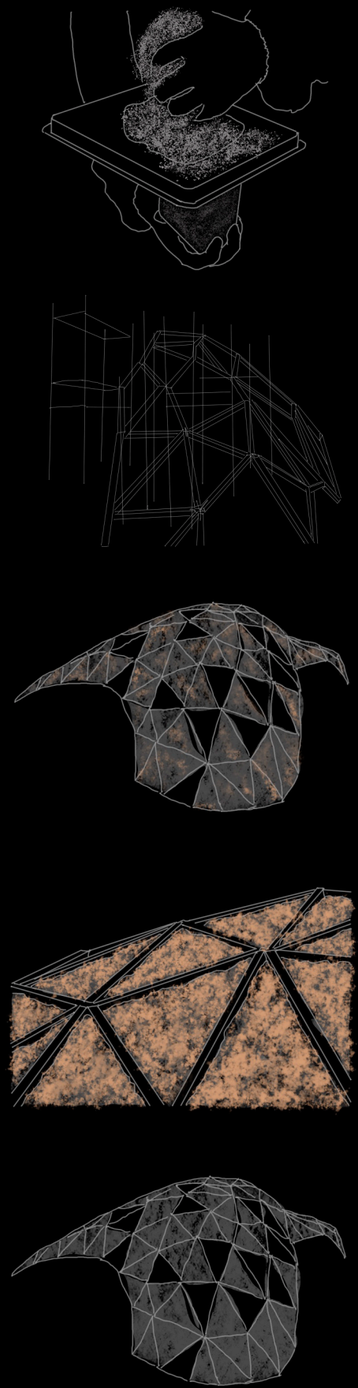


Fig. 2.17. A timeline showing the generational shift from "non living" to "living" projects and installations

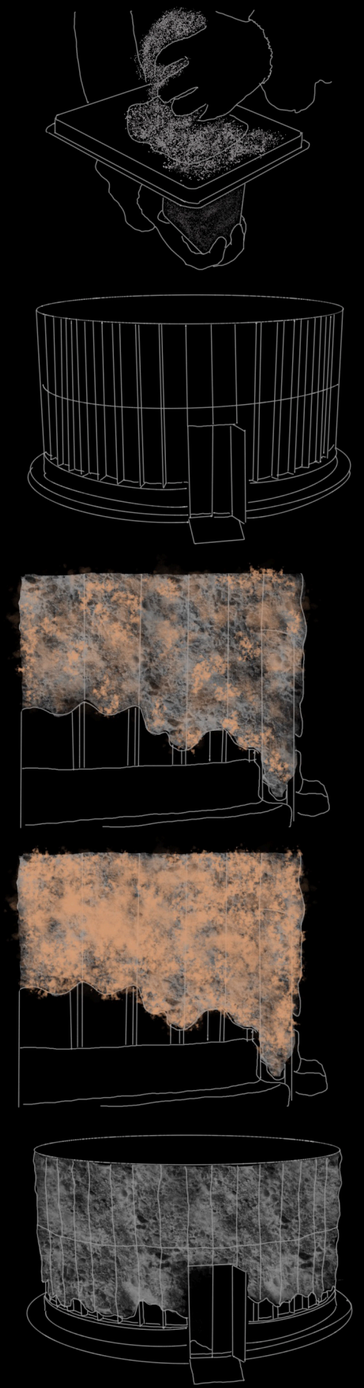
HY-FI



SHELL MYCELIUM



GROWING PAVILION

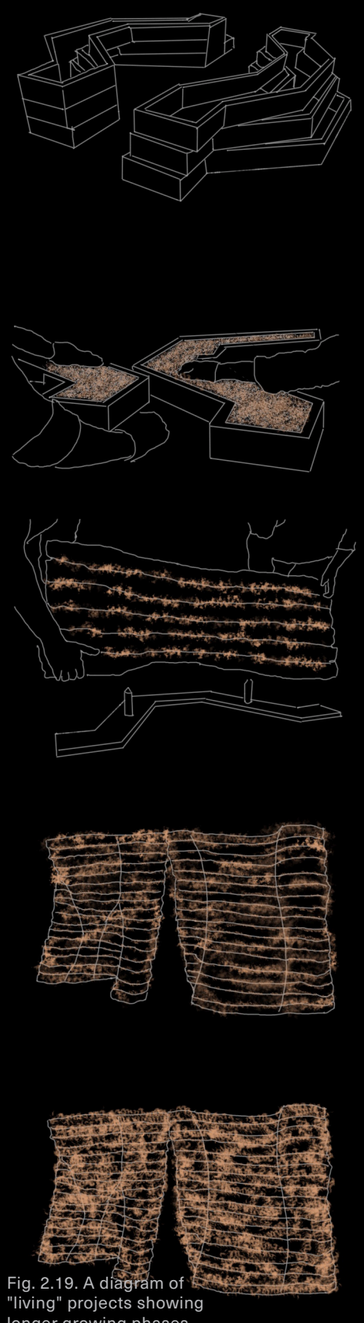


MONOLITO MICELIO

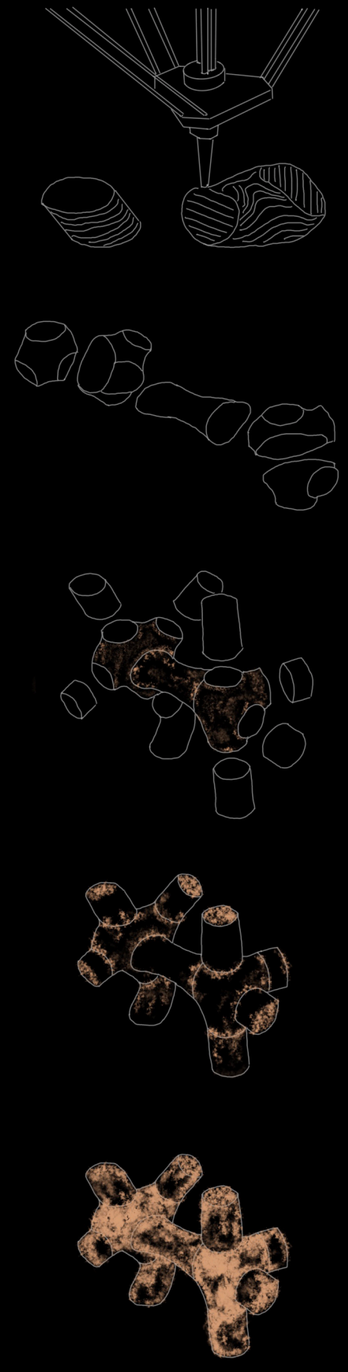


Fig. 2.18. A diagram of "non living" projects showing less periods of mycelium in its living state and often exhibited with dried mycelium.

LA PARETE FUNGINA



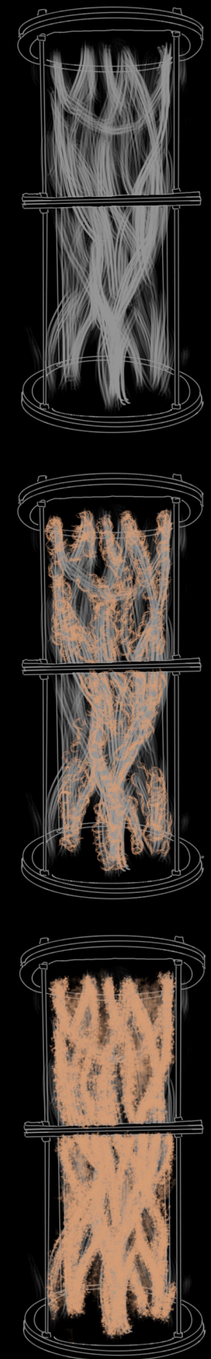
MYCERA



BIOKNIT



MYCELIUM TECTONICS



MYCELIUM ROPE



Fig. 2.19. A diagram of "living" projects showing longer growing phases and being displayed while mycelium is alive.

However, shifting from the likes of mould fabrication and monolithic structures, the living mycelium approach introduces a new set of unique innovative building methods influenced by the behaviour of the living organism. Through their works, there has been significant success in the effective integration of the tools of synthetic biology into architecture. The interdisciplinary approach of synthetic biology offers new advantageous ways of combining living systems with the robustness of traditional tools or materials to produce genuinely sustainable and environmentally responsive architecture.[96] This approach includes the integration of biological processes, computer-aided design methods with biotechnological modifications and analyzing tools to utilize natural functions that could modify or improve the functional properties of manufactured mycelium-based composites.[97]

Another emerging solution to address the drawbacks presented in current mycelial approach is the application of surface growth on textiles, in which mycelium is utilized in a way that it dries and joins with the supporting textile framework completely. The specialized approach of material collaboration explores the interaction between textiles and living organisms as a relatively new discipline that studies the interaction between two distinct materials and their ability to work as one.[98] The developing field of mycelium construction also demonstrates the strengths of multi-scalar assembly functions of living mycelium as a means of architectural assembly without the need for joinery materials. Due to its ability to expand its hyphae branches into complex, linear patterns, to create solid, bonded surfaces, designers are attempting to translate this biological mechanism into much larger-scale construction applications.[99]

In addition to the contributions of today's technological advancements to the development of living mycelium-based works, another benefit of switching to this living approach provides a solution to one of the primary problems that the traditional construction methods of fungal architecture faced: its wasteful formwork. Regardless of the minor active energy inputs needed to cultivate fungi, the projects' reliance on plastic and non-biodegradable molds has presented an ethical dilemma. *Monolito Micelio*, for example, faced the issue of plastic-lined plywood and nylon fabric used as formwork, resulting in non-recyclable waste.[100] Another methodology featured in the living category of mycelium construction is the benefits of 3D printing integration to mycelium-based composites. The 3D printing

96. Campbell et al., "Modular Mycelia." 4

97. Attias et al., "Mycelium Bio-Composites in Industrial Design and Architecture." 6

98. Biala and Ostermann, "Mycostructures—Growth-Driven Fabrication Processes for Architectural Elements from Mycelium Composites." 4

99. Campbell et al., "Modular Mycelia." 5

100. Dessi-Olive, "Strategies for Growing Large-Scale Mycelium Structures." 5

101. Mohseni et al., "Three-Dimensional Printing of Living Mycelium-Based Composites." 4

technique allows the fabrication of intricate forms and reduces waste from mold and large formworks. According to Mohseni, extrusion is one of the least energy-intensive manufacturing techniques, making it a promising alternative for low-cost and low-energy manufacturing of fungal materials.[101]

To further expand on the benefits offered by the living approach mentioned above, the paper delves into five specific strategies to analyze the potential, challenges, and knowledge gaps of such approaches in a much-detailed manner. This includes Myco-welding of conventional mycelium-based blocks (La Parete Fungina), Fibre reinforcement and welding of 3D-printed components (Mycera), Bio-collaboration of mycelium-based composite and bacterial cellulose (BioKnit), Bio-tectonic of living mycelium (Mycelium Tectonics), and Senso-aesthetics of mycelium's natural processes (Mycelium Rope). Moreover, the paper explores three key areas of focus to assess the potential and implications of living mycelium architectural approaches. First, biological utilization examines how the natural processes of mycelium are integrated and utilized into the design of each case study. Second, integral and lost formwork analyzes how initial formwork becomes a vital part of the final design iteration that enhances the characteristics of living mycelium. Third, material understanding and visual acceptance explore how the technical knowledge and aesthetic integration of living mycelium influence the perception and effectiveness of mycelium-based designs.

A set of parameters will be used to facilitate a consistent comparative analysis of the living projects mentioned above. Initially, Table 1 highlighted most of the factors that influence the viability of mycelium-based works. However, upon further research, Table 2 highlights specific parametres more relevant towards the "living".

PARAMETRES	DEFINITIONS
Fungal Species	The specific strand of fungi used to grow Mycelium that influences the properties of Mycelium on varying substrates. Specific strands produce fluffier Mycelium suitable for insulation purposes while others produce denser root fibers for higher structural properties.
Substrate Mixture	The type of organic materials used as a base for the growth of Mycelium. Substrates are usually bounded by the hyphae of fungi to provide hardening characteristics to Mycelium-based materials. The organic waste used often provides nutrients for the fungi to grow.
Site	The location of where the project or installation took place. Locating the project is important when considering availability of organic waste, environmental conditions, and availability of resources and labs.
Climate	The weather conditions of where the projects are located. Climate plays a vital role in determining the factors of growing Mycelium based on the site's humidity, precipitation, and temperature. Mycelium's current growth requirements rely heavily on controlled temperature.
Packing Method	The technique used to allow Mycelium to colonize the substrate. Most common method in the industry is packing into shaped molds while monolithic approaches are slowly gaining more attention.
Incubation Period	The number of days it takes for Mycelium colonization. Different fungi strains require different periods to fully colonize a substrate, so incubation is important to consider depending on the project timeline.
Drying Method	The method of killing the Mycelium to stop its growth. Drying fully colonized substrate not only prevents mushroom fruiting but also hardens the product to increase its strength.
Formwork	The type of structural support in which the inoculated substrate is placed. Different types of formworks are used depending on the architectural applications of the project.
Application	The method of using Mycelium-based materials. It initially started by using myco-materials as packaging but was advanced and is currently being used architecturally as insulation, envelope, and structural support.
Architectural Method	The varying approaches to achieve architecturally viable projects. Most commonly known to be used as blocks and panels that follow the brick-and-mortar approach but are slowly emerging into monolithic casting and bio-material assemblies.

Table 2. Set of parametres that are more relevant towards "living" projects.

PARAMETRES	DEFINITIONS
Post Treatment	The treatment that each Mycelium-based materials undergo once the substrate is colonized. Drying is typically the method to inactivate the fungi, but other approaches also produce different varieties aside from bricks.
Fungal Spawn Type	The form of the Mycelium source used to inoculate substrate. There are 2 types of spawns, grain spawn and liquid culture. Liquid culture is more common in living Mycelium projects as it can be mixed easily with different types of surfaces and directed-growth formworks.
Inoculation Method	It is the process of mixing the fungal strain within the base or substrate in which the Mycelium is expected to grow. Initially, the method was to always mix the strain with the substrate, but the living-growth approach introduced 3D inoculation and injection.
Growth Process	The process of growing Mycelium. The non-living projects typically grow Mycelium in molds but the shift to living Mycelium saw processes such as growth-directed fiber, binding growth, and more.
Growth Conditions	The condition of where Mycelium is allowed to grow. The selected projects display different types of growing conditions from indoor, controlled, sanitized, to outdoor, exposed, and uncontrolled. Light exposure is also another critical factor to avoid fruiting to occur.
Composite Exposure	The exposure of the growing of whole Mycelium composites. The main difference between non and living growth is that the living Mycelium composites are more prone and exposed to contamination due to not being fully enclosed to study the organic growth of fungi.
Containment	The type of enclosure (if contained) used to let the biological living growth process occur. Containing living Mycelium can be as simple as covering it with plastic while some methods include usage of incubators and organic formwork.
Sterilization Method	The killing of microorganisms to avoid contamination. Some common practices are sterilization of the substrate through pressure cooking, sanitization of growing environment, and containment of the composite.
Formwork Components	The materials used to support the living growth process of Mycelium in comparison to only providing structural support for the non-living Mycelium composites. Most of the living Mycelium projects use some sort of fiber-like material to direct the growth of Mycelium.
Hardware & Software	The advancement of hardware and software to assist the living growth of Mycelium. In comparison to the oven used in the non-living approach, the use of 3D printers, and digital modelling are slowly becoming integrated with the growing of Mycelium-based materials.

Chapter 3: The Living Mycelium: Case Studies



3.1 Myco-welding of Conventional Mycelium-Based Blocks: *La Parete Fungina*

Introduction: Myco-Welding

Recently, there has been increased attention to strategies for harnessing the capabilities of organisms in materials engineering. These include the creation of living biosensors, engineered drug-releasing organisms, and living function materials as potential means of sustainable material production with enhanced functionalities. One approach relevant to mycelium fabrication is the production of hybrid-living materials composed of live organisms grown on organic or synthetic scaffolds, which enable the harnessing of the organisms' material deposition and regenerative properties while providing control over factors such as form and substrate.[102] Unlike conventional modern construction methods and materials, natural living systems exhibit functions that include adaptation, self-repair, and self-organization.[103]

Derived from these functions, a fabrication technique referred to as myco-welding, or bio-welding in the field of mycelium architecture, has been gaining popularity. As shown in Figure 3.1.1, this specific technique involves assembling structures from modular units and growing them into monolithic wholes.[104] Myco-welding addresses some of the limitations faced in mycelium fabrication, which typically involves wasteful formwork to produce small individual units or single monolithic forms with restricted growth and transportation issues. The technique allows for the use of easily transported units to be fused into a final form in situ.[105] Evident in the previous projects explored such as *Hy-Fi* and *Shell Mycelium*, the mycelium-based composite blocks are usually supported by external factors such as wood or steel scaffold systems. Additionally, these blocks are adhered together with the use of conventional mortar. Due to mycelium's capabilities to infiltrate and bind various materials together through its hyphae networks, the organism is successful where rigid, natural bonds are required.

In preliminary experiments, mycelium demonstrated its ability to bridge up to 8 mm of gaps between organic substrates.[106] To utilize this and other distinctive mycelium properties, researchers have developed the system of myco-welding to benefit from its binding capabilities without the need for external binders or connections.[107] Myco-welding is initiated by the hyphal bonding process of mycelium, in which its branches intertwine and fuse together to form dense, interconnected solid connection networks. Hyphal bonding has been relevant in the field of mycelial architecture as it is the primary action that converts the loose substrate components into a single, solid

102. Sabrina C. Shen et al., "Robust Myco-Composites: A Biocomposite Platform for Versatile Hybrid-Living Materials," Materials Horizons 11, no. 7 (April 2, 2024): 5, https://doi.org/10.1039/D3MH01277H.

103. Campbell et al., "Modular Mycelia." 4

104. Dessi-Olive, "Strategies for Growing Large-Scale Mycelium Structures." 7

105. Shaina Saporta and Matthew Clark, "'Bio-Welding' of Mycelium-Based Materials," 1

106. Shen et al., "Robust Myco-Composites." 13

107. Ibid. 13

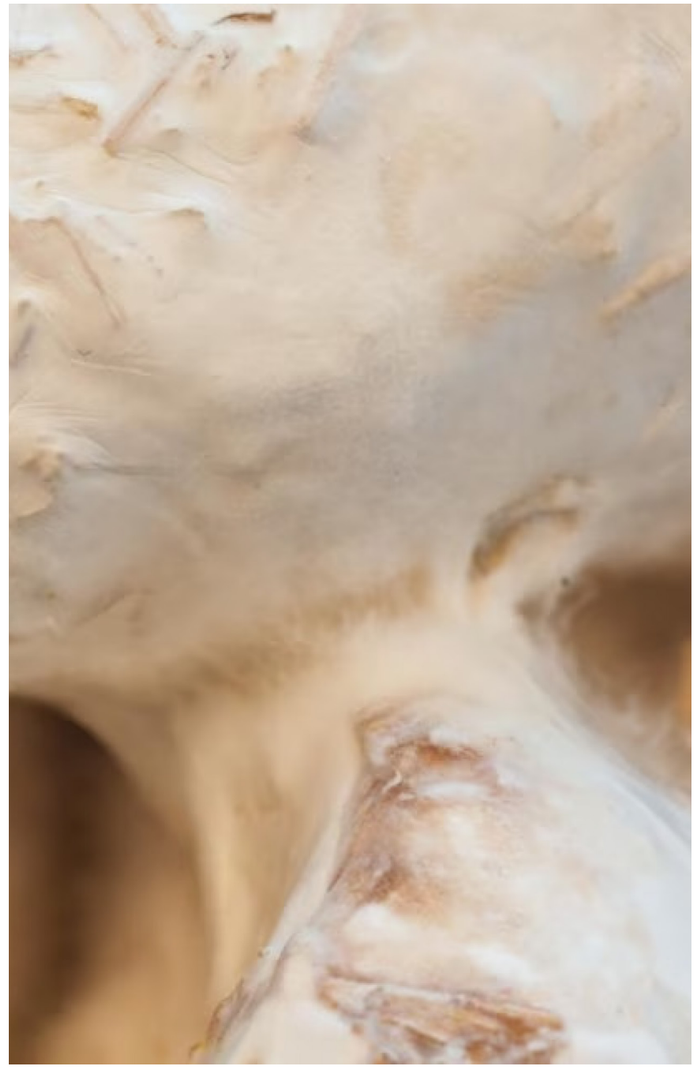


Fig. 3.1.1. A zoomed in photograph of hyphal bonding or "myco-welding" of two units.

block. Myco-welding, on the other hand, follows the same concept of hyphal bonding but instead, binds prefabricated mycelium-based blocks rather than the base substrates. The process of myco-welding, which utilizes the penetration and binding capacity of mycelium, plays a crucial role in this context and has been employed in some of the projects published in mycelial literature.[108]

The project *Modular Mycelia* by Campbell et al. shown in figure 3.1.2, is a notable example of how hyphal bonding can be utilized as a means of assembly. The project investigates the multi-scalar assembly system of modular mycelium-based spherical units offered by the myco-welding process, while outlining the challenges of translating the approach in a much larger-scale application such as contamination and growth requirements.[109] Furthermore, the goal of the project is not to produce functional architecture made entirely from fungi but rather to demonstrate the potential of a multi-scalar assembly system with mycelium as its binding element.[110] Additionally, the pioneering projects of David Benjamin and The Living named, *Voxel Bio-Welding* and *Jammed Bio-Welding*, highlights the myco-welding process as a dominant fabrication technique for large-scale applications (see figure 3.1.3 & 3.1.4). On both occasions, the projects involved inoculation and incubation of tiny mycelium-based blocks supported by a temporary formwork system. The structural support was later removed to showcase the free-standing prototypes due to the binding action of the mycelium.[111]

Although lacking in the structural characteristics if applied in larger-scale architectural projects, the approach evident in the projects mentioned provides insight into the potential of mycelium as a binding element of smaller, lighter architectural components. Amongst the related works in the field of mycelial architecture, the prototype, *La Parete Fungina* stands out as an exemplary project as it not only demonstrates the myco-welding technique explored above, but also expands upon the conventional fabrication methods applied in previous works. The project shares the same processes as some of the works mentioned above, driven by the process of myco-welding, however, the prototype *La Parete Fungina* addresses two of the main challenges faced by the smaller scale experiments: a larger-scale application and a waste-efficient reusable formwork structural system.

108. Ibid. 5

109. Campbell et al., "Modular Mycelia." 3

110. Ibid. 5

111. Bitting et al., "Challenges and Opportunities in Scaling up Architectural Applications of Mycelium-Based Materials with Digital Fabrication." 13



Fig. 3.1.2. A photograph of *Modular Mycelia's* modular units myco-welded together.



Fig. 3.1.3 (left). A zoomed in photograph of *Voxel Bio-Welding.*



Fig. 3.1.4 (right). A photograph of *Jammed Bio-Welding*

Overview: La Parete Fungina

La Parete Fungina was a demonstration of wall assembly systems that built upon the conventional methods of mycelium-based fabrication. The project tested the efficiency and effectiveness of myco-welding for its capacity to create complex formed wall structures from building units grown in reusable formwork systems.[112] Shown in figure 3.1.5, the project resulted in two undulating units that were approximately 1.2 metre tall with a design inspired by a serpentine geometry.[113] *La Parete Fungina*, a mycelium-based structure grown by graduate architecture students from the University of Virginia led by Jonathan Dessi-Olive, features undulating stripes of fungal blocks stacked on top of each other to facilitate and enable myco-welding (see figure 3.1.6).[114] [115] The experimental structure grown for biomaterial building exposition tested not only biological welding but also fabric forming techniques for growing large mycelium-based blocks and assembling them into efficiently formed wall structures.[116] Although the project aims to address the challenges of growing large-scale building components, it also touches upon the issues of materials ethics of energy and waste in the field of biomaterial production.[117]

Additionally, the project aims to demonstrate prototypes for reusable formworks systems capable of producing large myco-material building components in semi-controlled environmental conditions, taking inspiration from the traditional pre-cast concrete methods. By using myco-welding as a primary fabrication strategy, the project also intended to reduce the demand for long labour hours and minimize the risk of contamination in large colonies of mycelium-inoculated materials.[118] Furthermore, the project focuses on addressing two main issues often associated with the application of mycelium in architectural works: large-scale cultivation of mycelium into precise forms, and developing intuitive, reusable formworks that reduce waste byproducts in the growth and fabrication phases.[119]

112. Dessi-Olive, "Strategies for Growing Large-Scale Mycelium Structures." 17

113. Ibid. 14

114. Originally, two structures were produced in academic contexts in collaboration with students from the University of Virginia and Kansas State University. Along with the construction of La Parete Fungina, is L'Orso Fungino, which revisits the methodologies of in-situ, fabric-formed units that are stacked and post-tensioned. However, due to the stronger relevance of La Parete Fungina to the living methodologies explored in this paper, the case study will focus exclusively on this prototype.

115. Biala and Ostermann, "Mycostructures—Growth-Driven Fabrication Processes for Architectural Elements from Mycelium Composites." 513

116. Dessi-Olive, "Strategies for Growing Large-Scale Mycelium Structures." 9

117. Ibid. 1

118. Ibid. 9

119. Ibid. 7

Fig. 3.1.5 (right) An exterior shot of the prototype *La Parete Fungina.*

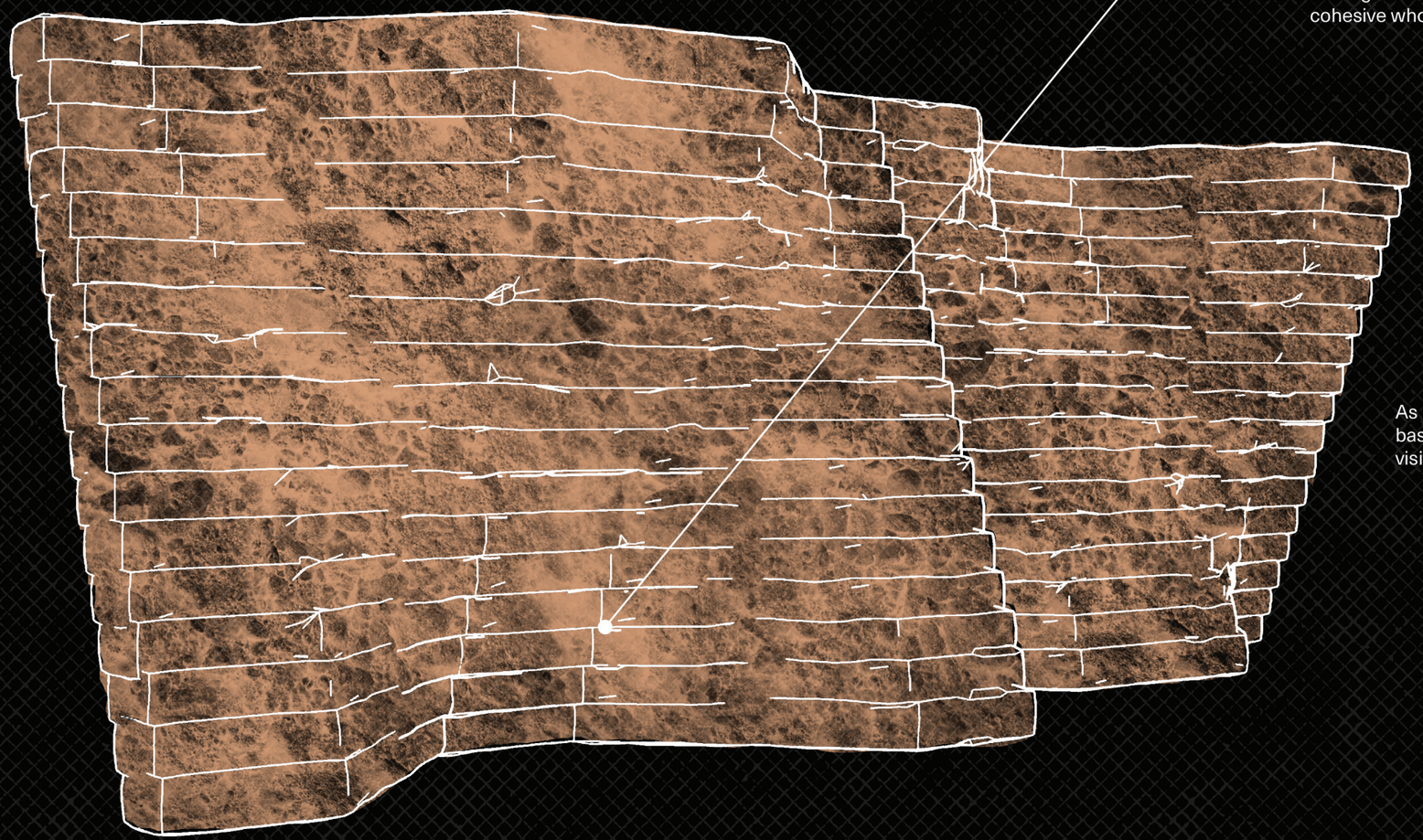
Fig. 3.1.6. (next page) The myco-welding process of *La Parete Fungina.*



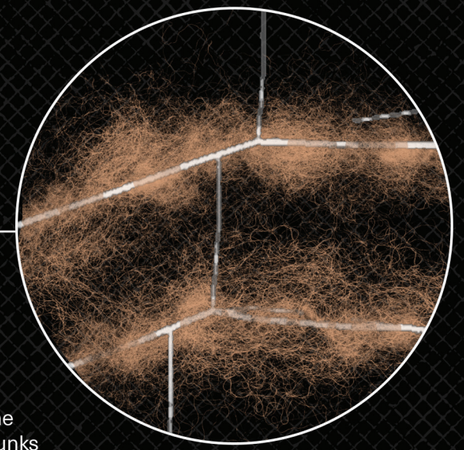
MYCO-WELDING

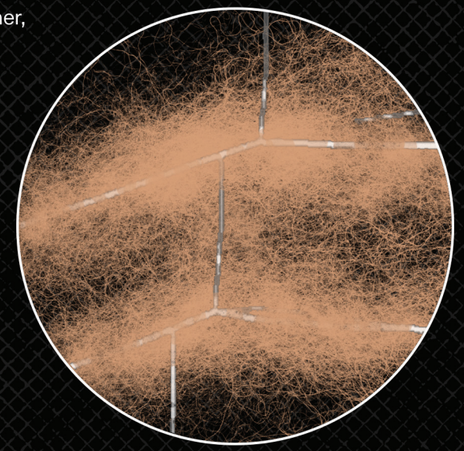
Myco-welding is the process of binding multiple elements together by allowing living mycelium's networks to expand and interlock with other hyphal networks nearby, intertwining and forming a strong, cohesive bond.

This process allows the construction of the wall prototype in-situ without the need for external binding agents such as traditional mortar.

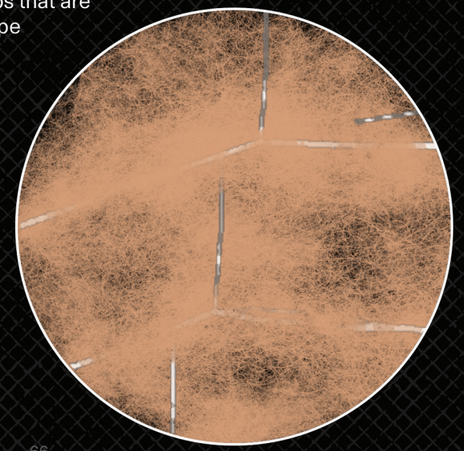


In the case of *La Parete Fungina*, the single block units referred to as chunks are stacked together while mycelium is still in its living state, and undergoes myco-welding as the networks from each blocks interlock with each other, turning the singular units into a cohesive whole.





As mycelium continues to colonize its base, it closes off the gaps that are visible in the wall prototype



Design and Process

La Parete Fungina consists of two wall units, each constructed from the seventeen V-shaped mycelium-based slabs myco-welded into three whole assembled components referred to as chunks.[120] The bio-welded mycelium-based components resulted in a 1.2-metre-high wall structure that was exhibited outside, that demonstrated resilience, withstanding outdoor conditions such as snow and wind.[121] The UVA's academical village's brick "serpentine-like" walls, a UNESCO World Heritage Site designed by Thomas Jefferson, served as the primary inspiration behind the geometry of the prototype that symbolizes the enclosure of the gardens behind each residence pavilion (see figure 3.1.7). Additionally, the project sought to emphasize the inherent properties of mycelium through their flexibility, stability, and material efficiency to promote environmental and human justice.[122] It is also important to note that scalability, the ability of mycelium to grow and expand consistently across different sizes and configurations, is the primary action that facilitates the process of myco-welding the blocks into the desired chunks. The project demonstrates that these scalable processes can be incorporated into an assembly system to manufacture individual elements, showcasing the potential of mycelium to form cohesive and expansive architectural structures as shown in figure 3.1.8.[123]



Fig. 3.1.7. The UVA's serpentine walls that inspired the geometry of the prototype.

120. Ibid. 10

121. Biala and Ostermann, "Mycostructures—Growth-Driven Fabrication Processes for Architectural Elements from Mycelium Composites." 513

122. Dessi-Olive, "Strategies for Growing Large-Scale Mycelium Structures." 8

123. Campbell et al., "Modular Mycelia." 3



Fig. 3.1.8. Another exterior shot of *La Parete Fungina.*

124. Dessi-Olive, "Strategies for Growing Large-Scale Mycelium Structures." 11-12

Fungal Species. For *La Parete Fungina*, a pallet of 65 bags containing 5 kgs each of living mycelium-inoculated substrates was provided by the mycelium manufacturer, Ecovative for the institution. The mixture of wet living materials contained a hemp substrate inoculated with the fungal strain of Phylum Basidiomycota, whose fruiting bodies resembled the brackets of reishi.[124]

Base/Formwork Components. To minimize waste, figure 3.1.9 shows the formworks for the prototype were designed as reusable slip-moulds. This strategy addresses the ethical issue of using plastic or other non-cellulosic materials in the production of the mycelial blocks (see figure 3.1.10).[125] Although made from recyclable wood and designed to be reused, the formwork would only be beneficial if there are multiple production of the wall prototypes. Otherwise, the reusable formwork would not serve any purpose and may still be considered as "waste" by many.

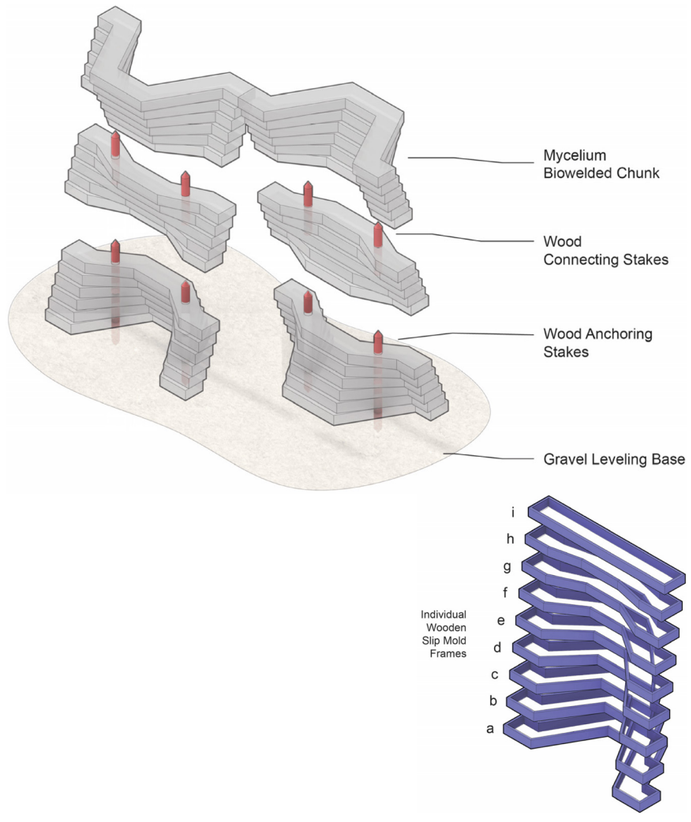


Fig. 3.1.9. (left) The reusable slip moulds and assembly system of the prototype.

Fig. 3.1.10. (next page) An assembly diagram showing the less formwork required prior to myco-welding

125. Ibid. 10

126. Ibid. 10

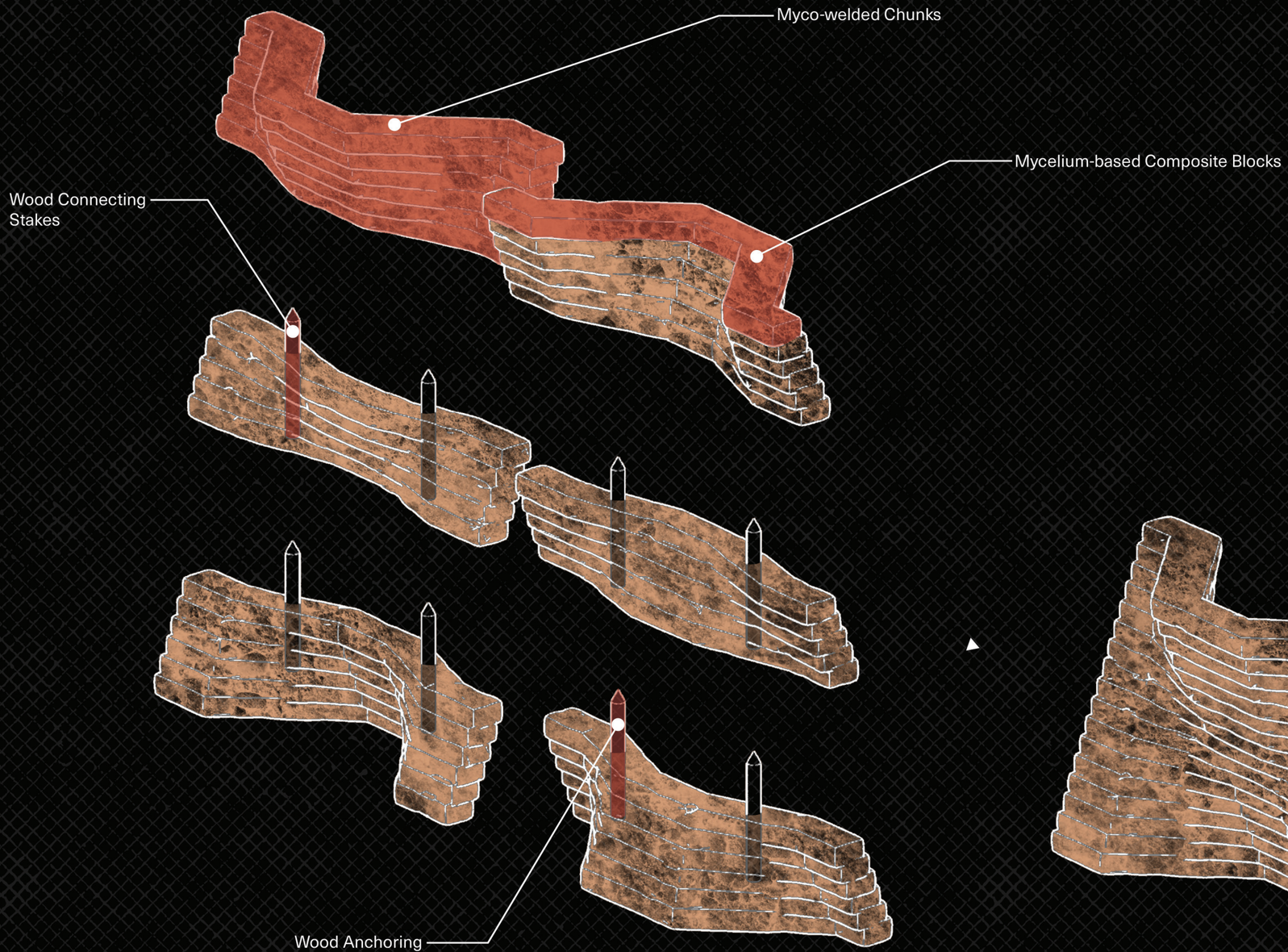
127. Ibid. 13

128. Ibid.10

Assembly Technique and Labour. The assembly techniques and processes employed in the project were designed to maximize efficiency but also collaborative to allow full involvement of the students in the cultivation and structure assembly (see figure 3.1.11).[126] To start the process of myco-welding the myco-blocks on site, the prefabricated blocks with living mycelium were stacked to form the "chunks" of five to six layers thick, with loose inoculated substrate, acting as the welding element, applied in between each slab to level the assembly. The slabs were gelatinous and fragile while being stacked due to not being dried to allow for living mycelium colonization and required careful handling under sanitary conditions that needed at least two students at a time.[127] Another strategy that was featured in the project is its utilization of a friction-based connection system that enables easy disassembly after the completion of the exposition.[128]



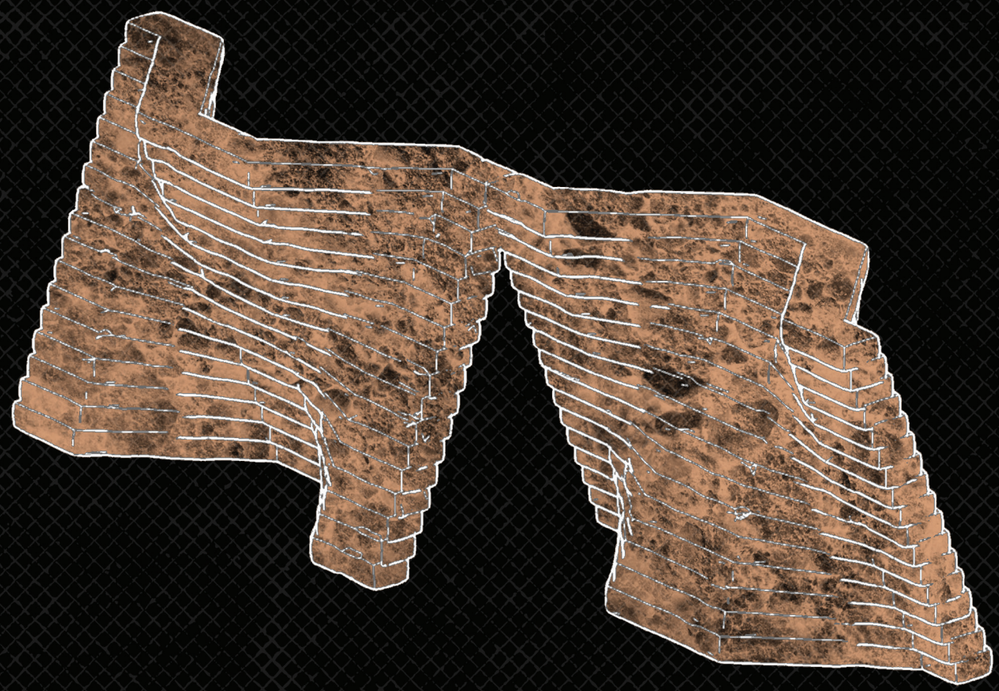
Fig. 3.1.11. Students from UVA stacking the "chunks" to initiate myco-welding.



STANDALONE

As the project employs strategies such as myco-welding and friction-based assembly system, the prototype required almost no supporting structure and is capable of standing on it own.

Typically, mycelium-based projects are faced with issues of wasteful formwork at the end of their life cycles, in this case, all components, including the binding agent, are compostable.



The design team of *Modular Mycelia* claimed that in comparison to their project's spherical units shown in figure 3.1.12, the wall design of *La Parete Fungina* benefits more from the process of myco-welding when stacked vertically, resulting in a more stable and solid structure while relying less on rigid formwork.[129] Furthermore, myco-welding presented several advantages that aligned with the number of students involved and how much time they could allocate for the project. Considering the time frame provided for the workshop, the two-phase growth process of myco-welding reduced the need for continuous labour hours, which are usually required for typical large in-situ monolithic casting techniques.[130]



Fig. 3.1.12. The multi-scalar modular system of *Modular Mycelia*

Growth Conditions. The inoculated slabs were kept in a clean, temperature-controlled, dark, and humid environment for roughly two weeks to ensure a healthy growth condition during the myco-welding process to grow them into monolithic-like masses.[131]

Contamination. Contamination prevention was a significant challenge in *La Parete Fungina* due to working with larger volumes of inoculated substrates compared to the smaller-scale bricks and blocks used in previous related works of myco-fabrication.[132] Unlike projects that worked with smaller scale units, *Modular Mycelia* for example, where contaminated composites can easily be removed from the colony, larger assemblies may complicate contamination management. Maintaining optimal environmental conditions such as moisture, temperature, and nutrition becomes more difficult as the volume of the composites increases.[133] To address such challenges, the slabs were covered in food-safe plastic film and covered with black plastic covering as a means of providing layers of contamination control.[134]

129. Campbell et al., "Modular Mycelia." 9

130. Dessi-Olive, "Strategies for Growing Large-Scale Mycelium Structures." 10

131. Ibid. 13

132. Campbell et al., "Modular Mycelia." 3

133. Ibid. 8

134. Dessi-Olive, "Strategies for Growing Large-Scale Mycelium Structures." 13

135. Ibid. 19

136. Ibid. 17

137. Ibid. 10

138. Ibid. 18

Reflection: Bio-welding as part of "The Living"

The project, *La Parete Fungina*, builds upon previous related works of building-scale structural parts and pavilions, expanding specifically on the concept of myco-welding. Through fully utilizing the hyphal bonding process in myco-welding, the project presented hybrid myco-fabrication techniques that minimized waste byproducts and addressed the challenge of cultivating large colonies of living MBCs into precise forms.[135]

Biological Utilization: Myco-welding

La Parete Fungina is recognized as one of the pioneering works of the living mycelium projects as it demonstrates a strong emphasis on the hyphal bonding of mycelium as its main assembly technique, also known as myco-welding. This biological strategy can be incorporated with well-established discrete elements, monolithic strategies, and 3D printing.[136] While the structure primarily consists of conventional moulded mycelium-based bricks, the project remains remarkable for its efforts to advance the utilization of mycelium's living binding capabilities, fusing not only the loose substrates as demonstrated in mycelial projects, but prefabricated mycelium-based blocks. One of the key findings from the projects is the observation of the thick layer overgrowth formed during the prolonged colonization of mycelium networks. The overgrowth acted as a hydrophobic defense layer for the fungal colony, both while alive and after drying, indicating that the strategy of myco-welding is an ideal choice for outdoor exhibitions.[137]

Compared to the more well-known project, the *Hy-Fi*, the strategies presented in the project involved assembling prototype structures that demonstrate the biological binding system of mycelium-based composites, instead of using traditional mortar. While the energy required to grow MBCs is lower than traditional practices, the prevalent use of waste formworks raises environmental concerns. Their reliance on carbon-emitting vehicles to transport fungal mixture for mycelium fabrication also highlights the need for a regional production model as a way of reducing transportation distances.[138] Thus, *La Parete Fungina* demonstrates the welding characteristics of living mycelium that allow for growth using standard units without the challenges of transportation and contamination control. As a result, the approach reduces the labour demands and lower uncertainties during on-site assembly. In addition to being more sustainable than conventional mortar, the natural systems of living mycelium could provide self-healing and self-regenerating binding systems that could reduce the requirements for maintenance and human labour.

Integral & Lost Formwork: Standalone

It is important to point out that most previous nonliving mycelium projects were designed to give the impression of achieving substantial structural integrity from mycelium composites alone. However, though they may look similar, they do not function comparably to traditional structural bricks or panels. Typically, these projects are cladded by non-structural mycelium bricks and blocks supported by concealed structural wood or steel formwork. In contrast, *La Parete Fungina* utilized the lightweight properties of mycelium-based composites by casting large, block elements in reusable wood and fabric mould system.

The project remains notable for its minimal use of base formwork in comparison to other mycelium-based projects consisting of bricks and blocks, as it relies on only two wooden anchors to stabilize the structure and relies on myco-welding to fully solidify the prototype. The lightweight mycelium-based composite blocks are also suitable for myco-welding as living mycelium lacks in structural integrity, also benefiting from the friction-based assembly system employed in the project. Furthermore, the project leveraged the myco-welding capabilities of living mycelium, minimizing the requirement for external binding agents in its construction. This process could open the discussion of the integration of living mycelium within non-structural components such as screening and façade systems that are non-load-bearing architectural elements.

Material Understanding & Visual Acceptance: Collaborative

The project established a scholarly discourse that raised public awareness of new biomaterial construction strategies, specifically, the unique biological capabilities of living mycelium. The projects *La Parete Fungina* and *L'Orso Fungino* demonstrated the capabilities of mycelium-based materials to adapt to different fabrication methodologies. The myco-welded chunks were highly informative due to their long growing time, demonstrating changes in colours and the formation of fruiting bodies. During its display period, the structure withstood wind and snow without collapsing or compromising the structure, showing the resilience and durability of the mycelium-based composites.[139]

Furthermore, the students had the opportunity to exercise their creativity and gain hands-on experience working with full-scale projects (see figure 3.1.13). In contrast to the form-making approach of the conventional mycelium fabrication approach, the craft of growing mycelium-based structures was developed collaboratively with the students and evolved throughout the entirety of the project.[140] By fostering a highly engaging experience with living mycelium throughout the project, a reciprocal exchange of resources and information was achieved, further developing the research of mycelial architecture. Dessi-Olive claimed that future bio-fabrication work should constantly integrate fungal growth, computational design, and digital fabrication to explore the constructive possibilities of mycelium-based materials. Therefore, engaging in more interactive and collaborative projects that explore living mycelium could significantly contribute to the development of the material in the architecture and construction industry.

Fig. 3.1.13. The collaborative experience offered by the project *La Parete Fungina.*

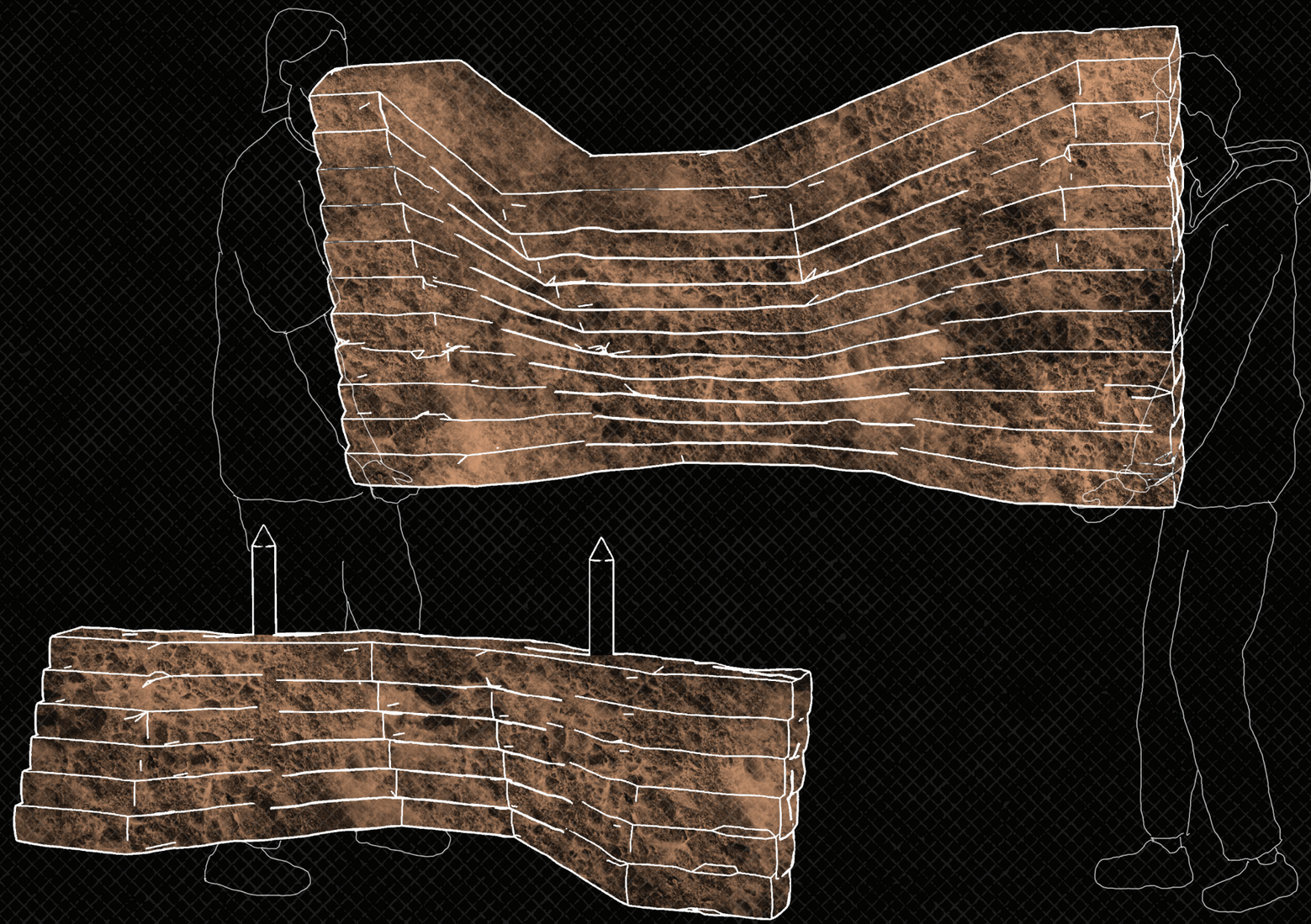
139. Ibid. 14

140. Ibid. 17

COLLABORATIVE

The collaborative experience offered by the workshop fosters for a stronger relationship between the students and the organism. The activity also provided the students a learning experience, allowing the participants to have a deeper understanding of mycelium's natural behaviours that can be used in developing the research further.

In addition, the students were exposed to the natural imperfections of mycelium's biological aesthetic and embraced its visual appeal without the need for finishing touches.



3.2 Mycelium as Fibre Reinforcement and Welding of 3D-Printed Components: *Mycera*

Introduction: Additive Manufacturing

Additive manufacturing processes that involve fabricating layered objects sequentially, have recently gained significant attention as a fabrication method. 3D printing, arguably the most applied technique included in the category, has been extensively discussed in bio-fabrication literature. However, only few projects have explored the incorporation of biomaterials in 3D printing methods.[141] In mycelium fabrication development, three-dimensional printing offers an alternative to conventional moulding techniques, producing unique shapes without the need for custom moulds (see figure 3.2.1).[142] The purpose of this research is to generate insights into the challenges, methods, and properties associated with the extrusion-based methods of biomaterials, either printed or grown on the surfaces, with the incorporation of living mycelium.

141. Elise Elsacker, Eveline Peeters, and Lars De Laet, "Large-Scale Robotic Extrusion-Based Additive Manufacturing with Living Mycelium Materials," Sustainable Futures 4 (2022): 100085, https://doi.org/10.1016/j.sftr.2022.100085.

142. Mohseni et al., "Three-Dimensional Printing of Living Mycelium-Based Composites." 2



Fig. 3.2.1 Different patterns of 3D-printed clay.



Fig. 3.2.2. Fruiting bodies on the coffee grounds and sawdust substrate mixture.

143. Ibid. 4

144. Fatima Ibrahim et al., "MycoCode: Development of an Extrudable Paste for 3D Printing Mycelium-Bound Composites," in Architecture and Design for Industry 4.0: Theory and Practice, ed. Maurizio Barberio et al. (Cham: Springer International Publishing, 2024), 505, https://doi.org/10.1007/978-3-031-6922-3_29.

According to Soh et al, extrusion is one of the least energy-intensive manufacturing techniques that provides low-cost and energy production of mycelium-based composites.[143] In recent years, several 3D-printed mycelium composites have emerged in the literature, exploring the potential of mycelium as fibre reinforcement in additive manufacturing. Shown in figure 3.2.2, a notable conceptual experimentation of clay and mycelium with varying substrates such as coffee grounds and sawdust for possible 3D printing base mixture was explored in the project, *Claycelium*. The work led by a team from Institute for Advanced Architecture of Catalonia in Barcelona paves the grounds in combining potential mycelium-based materials and clay in the additive manufacturing sector.[144]

Another project, *The Living Column* shown in figure 3.2.3 by Matthias Leschok investigates the biocompatibility of 3D printed Polyvinyl alcohol or PVA with mycelium-based composites. Previously investigated as a formwork for concrete, researchers in additive mycelium fabrication see great potential in the material as a formwork for mycelium-based composites as it can act as a nutrient source and is also dissolvable, allowing consolidation.[145] A few more examples of additive manufacturing of mycelium composites at large-scales include *Tree Column* by Blast Studio and *Proto-Mycokion*, both utilizing biopolymers as a nutrient source for mycelium to fabricate 3D-printed composites.[146]

The two projects also utilized the strategy of reaction-diffusion form-finding to assemble stacked printed objects with living fungal organisms.[147] A significant project that builds upon studies and incorporates the techniques such as the extrusion of mycelium composites, material mixtures of clay and mycelium, development of bio-hybrid architectural systems, and 3D printed composites from mycelium is *Mycera*. In addition to the multi-disciplinary approach employed in the project, the micro-scale level of research allows *Mycera* to fully understand the reinforcing capabilities of living mycelium within 3D-printed components.

145. Leschok and Dillenburger, "3D Printed Formwork for Mycelium Bound Composites." 7

146. Ibrahim et al., "MycoCode." 505

147. Elsacker, Peeters, and De Laet, "Large-Scale Robotic Extrusion-Based Additive Manufacturing with Living Mycelium Materials." 2



Fig. 3.2.3 A photograph of *The Living Column* made out of PVA and mycelium.

Overview: Mycera

Developed by the Shape Lab, a research group led by researchers, Julian Jauk, Lukas Gosch, Hana Vasatko, Ingolf Christian, Anita Klaus, and Milena Stavric at the Institute of Architecture and Media at the Graz University of Technology, *Mycera*, is an interdisciplinary design experiment that explores the biological compatibility of organic mycelium and inorganic clay materials (see figure 3.2.4). The key objective of the project is to make use of mycelium's complex networks as a natural fibre reinforcement to increase the structural integrity of unfired, 3D-printed clay elements and allow for the biological process of bio-welding the fired elements.[148] *Mycera* extends beyond the existing research by evaluating and reflecting on the structural findings of bio-based and digitally fabricated materials and observing their material distribution on a microscopic scale. By utilizing the biological welding and reinforcing functions of mycelium in its living state, the project aims to incorporate natural growth processes as an additional parameter in architectural design.[149]

The project is a unique three-dimensional form of bonded elements made of clay that represents an bio-fabrication technique in mycelium research for sustainable architectural applications.[150] The project aims to promote an interdisciplinary approach influenced by the latest developments in mycology, bio-based materials, clay, and 3D-printing, with a focus on the extraction and utilization of highly accessible and widespread materials, clay and mycelium.[151] Shown in figure 3.2.5, the interdisciplinary research approach practiced in *Mycera* combines digital manufacturing that allows for controlled material distribution, with mycelium growth facilitating the microscopic fibre connections.[152]

148. Alessandro Severi, "MyCera | 3D Printing Mycelium Reinforced Structures," 3D Printers | WASP, September 5, 2023, https://www.3dwasp.com/en/mycera-3d-printing-mycelium-reinforced-structures/.

149. Julian Jauk et al., "MyCera. Application of Mycelial Growth within Digitally Manufactured Clay Structures," International Journal of Architectural Computing 20, no. 1 (March 1, 2022): 2, https://doi.org/10.1177/14780771221082248.

150. Jauk et al., "MyCera. Application of Mycelial Growth within Digitally Manufactured Clay Structures." 1

151. Ibid. 1

152. Julian Jauk et al., MYCERA A Sustainable Future Building Material Consisting of Clay and Mycelium, 2021.



Fig. 3.2.4 Mycelium growing on the printed elements of the project *Mycera*.

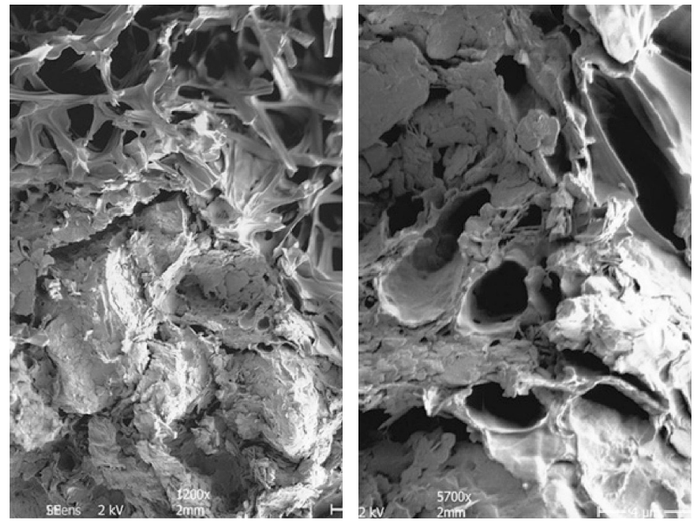


Fig. 3.2.5 Microscopic images of the fibre connections of living mycelium.

Design and Process

The study primarily focuses on the product the research team referred to as “Combined Structure.” Two distinct 3D-printed components inoculated in two different methods make up the Combined Structure (see figure 3.2.6). The first element, called “nodes,” are 3D-printed mycelium-based composites that handle tension and shear forces, while the “bar” elements are components crafted from fired clay (see figure 3.2.7). The bar elements, made from fired clay, primarily bear pressure load, while the node elements that consist of unfired clay and a larger percentage of mycelium content are more capable of bearing tensile and torsion loads.[153]

153. Jauk et al., “MyCera. Application of Mycelial Growth within Digitally Manufactured Clay Structures.” 2



Fig. 3.2.6. (next page) The growth process of Combined Structure.

Fig. 3.2.7. (left) Photographs of 3D printed bars and nodes.

154. Mohseni et al., “Three-Dimensional Printing of Living Mycelium-Based Composites.” 6

155. Jauk et al., “MyCera. Application of Mycelial Growth within Digitally Manufactured Clay Structures.” 2

The design team primarily investigated a unique, two-phase multi-material manufacturing method to fabricate the mycelium-based composites with enhanced porosity and intricacy, introducing a different approach from the more popularized mold-and-baked brick mycelium-based composites. The method provides solutions for existing 3D printing limitations by incorporating a secondary material to act as a structural support to create the complicated structure for the experiment. The core is completely extruded, so the aim of the research is to find a new fabrication setup to shape and support the structure with the use of complex mycelial networks.[154] Shown in figure 3.2.8, multiple material mixtures were created, as well as samples of different geometries that specifically respond to different properties based on the respective material and fabrication processes. The project was conducted in four phases: material experimentation, hardware and software setup, testing and measurement, and the fabrication of the Combined Structure.[155]



Fig. 3.2.8. Images of the initial samples conducted before fabricating Combined Structure.

COLONIZE

The illustration of the colonization and growth process of the prototype Combined Structure demonstrates the growth of mycelium from two elements inoculated in different methods.

The prototype also saw higher mycelium density in areas where the two methods of inoculation meet. The hollow core of bars are filled with inoculated substrates while the solid nodes are inoculated with liquid spawn on the surface, resulting in higher mycelium colonization in the connecting points



Fungal Species. In this project, two mycelium strains were initially considered, *Ganoderma Lucidum* and *Pleurotus Ostreatus*. Several early experiments indicated that *Ganoderma Lucidum* more frequently faced contamination problems, while the latter has proven to be a more suitable option for lesser contamination occurrence. Furthermore, it is more effective in digesting varieties of substrates, with a faster growth rate and rapid colonization rate, especially in its second growth phase. The researchers inoculated the material mixtures with ten percent of the selected mycelial strain to balance the acceleration of fungal growth without compromising the quality of the outcome.[156]

Substrate Mixture. The substrate mixture, a key component for mycelial growth and structural integrity of the project, consisted of 87.5% clay and 22.5% sawdust.[157] The next step would be finding the optimal material viscosity for the 3D printer. The main objective in this phase was to find the optimum ratio of organic and inorganic parts which have the following properties: 1) ensures enough nutrition for homogenous mycelial growth, 2) ensures that the mixture meets the required and specific elasticity and viscosity for 3d printing fabrication. The mixture was refined to keep the water amount as low as possible to reduce drying time and shrinkage issues.[158]

Formwork Components. The structural formwork into which mycelium grows was entirely made of 3D-printed components. It is important that the formwork components are non-toxic and must withstand sterilization, often with chemicals such as bleach and alcohol.[159] The initial step in the 3D-printing fabrication process was to sieve the sawdust to ensure that a particle size not more than two millimeters is obtained to avoid nozzle blockage of the printer. Developing an extrudable paste that has form stabilization qualities is an important step in 3D-printing fabrication. Altering the water content as well as using modifiers are some options commonly used to change the mixture's viscosity.[160] Both clay and sawdust were pulverized and blended with water by a mixing machine, although wood-based composites have also been gaining attention as a successful base for extrusion.[161]

156. Ibid. 3

157. Ibid. 7

158. Ibid. 3

159. Leschok and Dillenburger, "3D Printed Formwork for Mycelium Bound Composites." 3

160. Mohseni et al., "Three-Dimensional Printing of Living Mycelium-Based Composites." 4

161. Leschok and Dillenburger, "3D Printed Formwork for Mycelium Bound Composites." 5

162. Jauk et al., "MyCera. Application of Mycelial Growth within Digitally Manufactured Clay Structures." 8

163. Ibid. 4

164. Eugene Soh et al., "Development of an Extrudable Paste to Build Mycelium-Bound Composites," Materials & Design 195 (October 1, 2020): 109058, https://doi.org/10.1016/j.matdes.2020.3.

Hardware and Software. The geometry of the Combined Structure was defined by a design software plugin that was abstracted to an axis diagram in which the axes were rebuilt with cylindrical objects and nodes. The final design of the structure before mycelium colonization is a reflection on the possibilities of combining material qualities with digital fabrication.[162] The visual scripting interface Grasshopper for Rhinoceros 3D was the primary tool used to generate the G-Codes for the project, which contains information regarding extrusion rate and toolpath directly within the environment used for designing the prototypes (see figure 3.2.9).[163] Recent works shown in figure 3.2.10 also showcase other 3D printing methods of organic composites such as inkjet printing of liquid droplets, lamination of sheets, laser beam processes, and fused deposition modelling on heated filaments.[164]

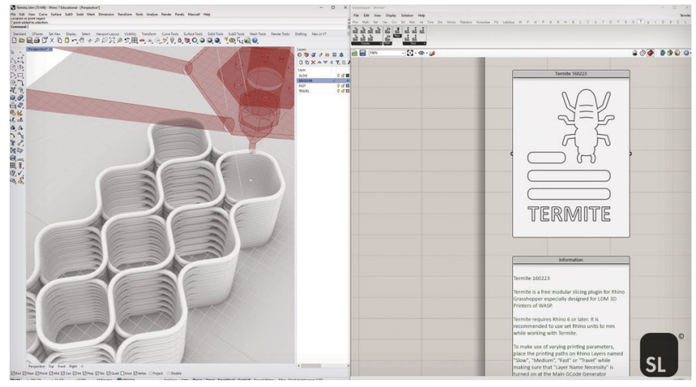


Fig. 3.2.9 The software, Grasshopper, as the main tool for generating patterns for 3D printed elements.



Fig. 3.2.10. Different methods of inoculating 3D printed elements with mycelium.

Inoculation Method. A common practice in the clay and mycelium fabrication follows three main stages of mycelium cultivation: inoculation, growth and ceasing.[165] For *Mycera*, the next step after printing is to wrap the elements in a tear-resistant aluminum foil and autoclave at 120 degrees Celsius for approximately 120 minutes as a method of sterilization. Once the materials were printed and sterilized, inoculation was carried out in two different methods. A liquid mycelium spawn was dispersed on the surface of the solid node objects for surface colonization, whereas the hollow ones were filled with inoculated substrate to fill the cores.[166]

Assembly Technique and Labour. The Combined Structure features the interlocking process of mycelial networks, also known as myco-welding explored in the previous chapter, to assemble the nodes and the bars during its growth process. The mycelium fibers of the living mycelium dispersed and filled formed connections by expanding its hyphal network and bio-welded adjacent elements together.[167] Shown in figure 3.2.11, the mycelium colonization that occurred from dispersing liquid spawn on the bar surfaces expands its networks and integrate with the fibres from the colonization that occurred in the inoculated substrate mixture filled within the hollow core of the nodes. The mycelial connections were able to tolerate uneven contact between surfaces and fill visible gaps, similar to how mortar functions in traditional construction methods (see figure 3.2.12).[168]



Fig. 3.2.11. (next page) Illustrations of mycelium penetrating through the small gaps between two elements.

Fig. 3.2.12. (left) Mycelial growth on the surfaces of the 3D printed elements.

165. Mohseni et al., "Three-Dimensional Printing of Living Mycelium-Based Composites." 4

166. Jauk et al., "MyCera. Application of Mycelial Growth within Digitally Manufactured Clay Structures." 8

167. Mohseni et al., "Three-Dimensional Printing of Living Mycelium-Based Composites." 5

168. Jauk et al., "MyCera. Application of Mycelial Growth within Digitally Manufactured Clay Structures." 8

169. Ibid. 5

170. Severi, "MyCera | 3D Printing Mycelium Reinforced Structures."

171. Jauk et al., "MyCera. Application of Mycelial Growth within Digitally Manufactured Clay Structures." 6-7

172. Ibid. 9

Product Testing. Lastly, extensive testing was conducted to evaluate the mechanical properties of the mycelium-composite Combined Structure. Two distinct tests were carried out: 1) the tensile strength test along the extrusion axis and 2) the binding force test between the printed layers. Some test findings showed a significant increase in average maximum tensile strength values of 66.62% for the samples with mycelial growth compared to those without (see figure 3.2.13).[169] The findings confirmed the hypothesis by showing an increase of maximum tensile strength values along the connections between the single layers by 32.34%.[170]

The samples with wall thicknesses ranging from 2.5-9.5 mm showed successful mycelial growth through 3D-printed clay walls. The study suggested that mycelial colonization is possible even at low porosity structures. Further investigation documented by a microscope revealed a clear differentiation between the fiber-like organic particles, hyphae, and inorganic clay particles, suggesting that mycelium is capable of partially penetrating inorganic components in its search for nutrients, forming a tube-like porosity through growth.[171] The high increase of tensile strength resulted from the growth process that took place after printing, as seen in the gathered microscopic imaging of hyphal penetration through clay, a specific type of intelligent fiber distribution that could not have been achieved with a non-growing material (see figure 3.2.14).[172]

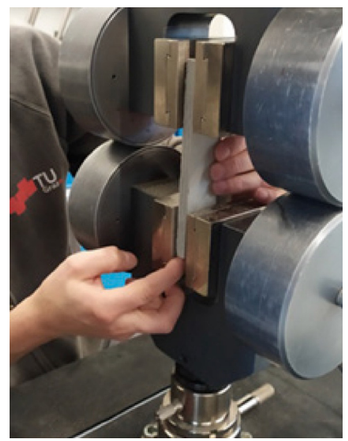


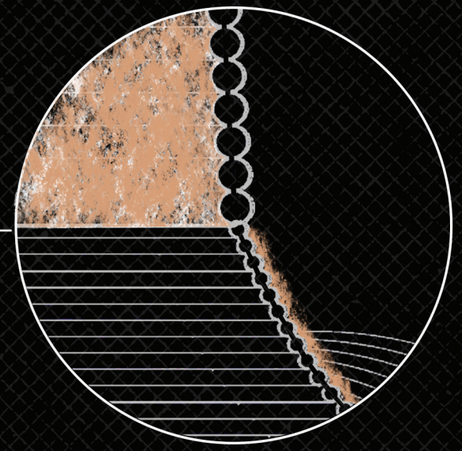


Fig. 3.2.13. Tools used to test the structural capabilities of 3D printed elements with mycelium.

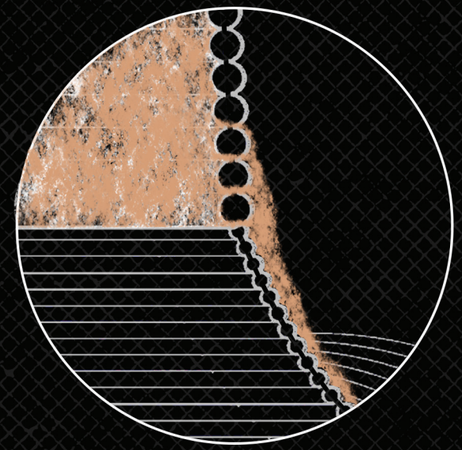
PENETRATE

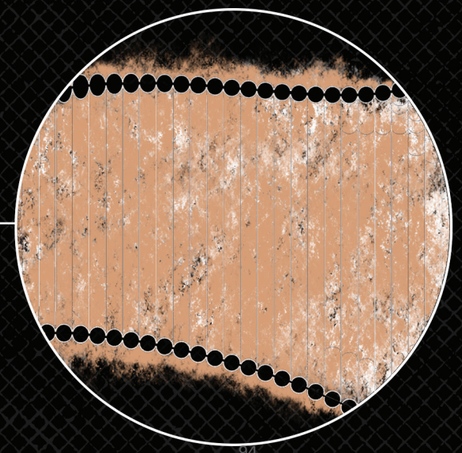
As discussed in the previous diagram, this diagram illustrates the section detail of two inoculation methods leading to higher density areas of mycelium colonization. In addition, mycelium showed its capability to penetrate through the tiny gaps present in the 3D printed elements.





Growth on areas where surface inoculation and substrate inoculation meet





Mycelium penetrating the gaps of the 3D printed elements



Fig. 3.2.14 A photograph of the hollow cores being colonized by the mycelium inoculated substrates.

173. Jauk et al., MYCERA A Sustainable Future Building Material Consisting of Clay and Mycelium.

Reflection: Fibre Reinforcement as part of "The Living"

The project offers insights into integrating the natural growth process of mycelium with the advanced digital fabrication techniques to address the current global waste management and carbon emissions. The following are a few takeaways that highlight the significance of the living mycelium in the project.

Biological Utilization: Penetrate

One key learning from the project Mycera is that living mycelium not only enhances the structural performance of 3D-printed clay but also facilitates a unique natural fabrication process of myco-welding that allows various components to bond seamlessly. Identical to the previous project *La Parete Fungina's* utilization of mycelium's ability to bio-weld the node and bar elements together, the project benefited from the growing complex networks of living mycelium. The assembly of these composites in a living state allowed the fibers from the surface of the mycelium wall to expand and integrate with the colonized substrate from the adjacent hollow bar components. Furthermore, this observation challenges the conventional practice that the growth and colonization of the fungal networks are restricted to substrates in closely packed forms. The welding process that occurred in Mycera demonstrates the complex network behaviour of living mycelium that facilitated the expansion and merging of two spawn sources from different locations. After accomplishing sufficient research, the proposed materials could be a substitute for cement-based binders.[173]

Integral & Lost Formwork: Reinforcement

The concept of biohybrid collaboration in the Mycera highlights the interdisciplinary approach of methods and ideas derived from the intersecting fields of architecture, mycology, biomaterials, clay, and 3D printing. The project primarily focused on not only advancing the research on mycelium and clay but also creating unique architectural systems integrating the two, showcasing the potential of the collaborative approach between organic and inorganic. The incorporation of living mycelium into 3D-printed unfired clay elements revealed an unrecognized capability for mycelium to penetrate the porous walls of the clay structures. This method resulted in a significant enhancement of the structural integrity of the clay components by providing additional fibre reinforcement. Furthermore, 3D-printing fabrication of mycelium-based composites presents the potential to form shapes for enhanced air circulation to support mycelium growth within the geometry. The experiments from

Mycera and related previous works revealed the potential of using mycelium to prevent cracking during biomaterial extrusion.[174]

Additionally, one of the main objectives of the research is to explore the potential of mycelium as a structural element in architectural applications. The tests confirmed the hypothesis of the research group as they revealed remarkable results in maximum tensile strength for samples with mycelial growth, further validating the effectiveness of the organism in enhancing structural performance. It is undeniable that mycelium's lack of structural properties has hindered its widespread adoption in contemporary construction and architectural practices. Thus, these findings suggest that mycelium could be capable of providing valuable structural reinforcement. Although it may not replace primary structural elements, its role in enhancing structural properties could significantly advance the field of mycelium architecture.

174. Elsacker, Peeters, and De Laet, "Large-Scale Robotic Extrusion-Based Additive Manufacturing with Living Mycelium Materials." 13

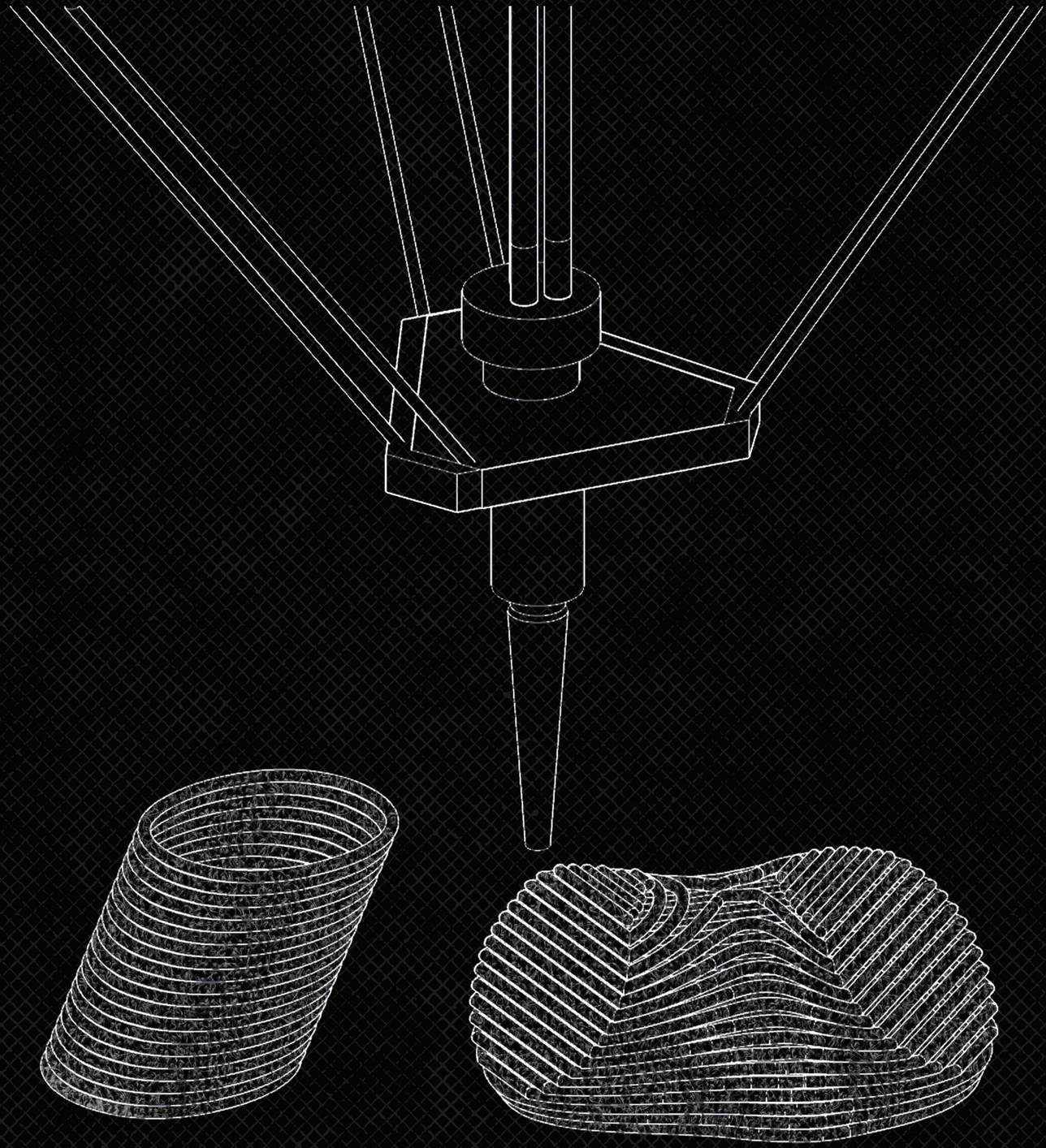
Material Understanding & Visual Acceptance: Myco-Extrusion

The project inspires further exploration into the collaborative systems offered by living organisms by incorporating various biomaterials and bio-fabrication methods (see figure 3.2.15). While most projects might hesitate to explore multiple unfamiliar elements, these teams and researchers welcome the risk of failure as a necessary step to advance the research of living mycelium, revealing a multitude of new and unexplored findings. Furthermore, the project aims to fully understand how the natural processes offered by mycelium can be harnessed to enhance sustainable architecture by focusing on the microscopic level of study. Through this scale, the project effectively demonstrates how specific biological living processes can influence traditional fabrication techniques. The project continues to inspire future research and development of environmentally friendly construction approaches by showcasing how natural and synthetic materials collaborate.

Fig. 3.2.15. The use of external tools for additive manufacturing of mycelium-based projects.

MYCO-EXTRUSION

The project inspires further exploration for employing hybrid techniques as showcased in the project. The use of additive manufacturing, 3D printing to be specific, introduced multiple unique findings, showing the adaptive nature of mycelium and its compatibility with other materials.



3.3 Bio-collaboration of Mycelium-Based Composites and Bacterial Cellulose: *BioKnit*

Introduction: Biohybrid Knitting

Biohybrid material systems, also known as bio hybridization, is the method of combining biological organisms alongside synthetic materials such as polymers or ceramics to create composite structures.[175] Precedents such as *Mycera*, the case study analyzed from the previous chapter, is a good example of incorporating multiple material systems, clay and living mycelium to be specific, and investigate their compatibility. As researchers seek biohybrid strategies of incorporating both biological and non-biological components toward sustainable construction approaches, the development of mycelium-based systems are becoming increasingly apparent.[176] The use of knitted fabric, in mycelium fabrication, as seen in previous knitted works of Yogiaman and Scott et al., is growing due to its high bio-compatibility with microorganisms, scalability, and its ability to create lightweight and complex structures (see figure 3.3.1).[177] This specific biohybrid approach integrates mycelium-inoculated substrate mixtures into the hollow cores of tubular knitted textiles that allows for creation of unified architectural structures.[178] The ability of mycelium to grow through the small openings in the textile's surface is a function that only living organisms can offer.[179]

175. Armand Agraviador et al., "Computation and Material Investigation in the Design of Biohybrid Textiles towards Architectural Integration," 2

176. Agraviador et al., "Computation and Material Investigation in the Design of Biohybrid Textiles towards Architectural Integration." 2

177. Jane Scott et al., "Possibilities of Mycelium Biofabrication in the Built Environment," 2

178. Agraviador et al., "Computation and Material Investigation in the Design of Biohybrid Textiles towards Architectural Integration." 3

179. Biala and Ostermann, "Mycostructures—Growth-Driven Fabrication Processes for Architectural Elements from Mycelium Composites." 512



Fig. 3.3.1. Mycelium colonization on knitted textile.

180. Christine Yogiaman et al., "Knitted Bio-Material Assembly" (ACADIA 2020: Distributed Proximities, Online and Global, 2020), 60, https://doi.org/10.52842/conf.acadia.2020.1.058.

181. "Nienke Hoogvliet's Sea Me Furniture Is Made from Woven Algae," Dezeen, July 17, 2016, https://www.dezeen.com/2016/07/17/sea-me-furniture-studio-nienke-hoogvliet-design-seaweed-woven-algae-table-chair/.

182. Agraviador et al., "Computation and Material Investigation in the Design of Biohybrid Textiles towards Architectural Integration." 2

183. Ibid. 3

184. Jane Scott et al., "Knitted Cultivation: Textiling a Multi-Kingdom Bio Architecture," 2022, 3, https://doi.org/10.1201/9781003023555-1.

The knitting process of yarn, often incorporated with biomaterials such as mycelium, bacterial cellulose, and bioresin, is modified to produce various textures and structures, which directly influence performance aspects of a structure in terms of tensile strength and extensibility.[180] [181] Shown in figure 3.3.2, the overall knit system serves as permanent formwork, as well as an assimilative textile surface for mycelial growth, presenting an opportunity to rethink traditional building construction approaches from assembly to growth.[182] Industrial knitting of textiles is ideal for biohybrid use as it allows for the incorporation of variable properties within a continuous material. The sophistication of the knitting technology also enables the fabrication of shaped panels, 3D tubes, or preforms that combine both. Additionally, the adjustability of fabric parametres during design and fabrication results in improved mechanical performances, combining the tensile strength of knitted fabric with the compressive strength of mycelium composites.[183] Another benefit offered by the knitting approach is its ability to adopt curved forms under multi-directional forces, suitable for developing intricate shapes. This enables the production of zero-waste knitted scaffolds designed in complex 2D and 3D forms, a challenge often faced by the traditional approach of brick-and-panel mycelium-based fabrication.[184]



Fig. 3.3.2 A photograph of the lost knitted formwork of mycelium colonization

There are a few notable precedents that exemplifies the unique biohybrid approach of combining flexible, shaped knitted formwork with the complex living networks of mycelium. One of them is *Knitted Mycelium Composite Structure*, by Yogiaman et al., a V-shaped knitted textile filled with mycelium-inoculated mixture aimed to augment the final material properties while providing formal freedom to the designers (see figure 3.3.3).[185] As shown in figure 3.3.4, *The Living Room* by Dr. Jane Scott demonstrates how mycelium textile fabrication can make use of waste materials from local industries to grow large structures with minimal environmental impact (see figure 3.3.4). The project by Scott and her team transitioned to 100 percent waste material fabrication, using knitted wool as a base for mycelium growth. The study allowed Scott and her team to identify the potential of knitted textile as a sacrificial mould, a base formwork that integrates with mycelium and becomes part of the final structure in mycelium fabrication, enhancing the mechanical properties of the composite by providing an external surface for mycelial colonization and increasing air access for denser fungal growth.[186] To provide a better understanding of the opportunities and challenges offered by the biohybrid collaboration of textiles and living mycelium, the project *BioKnit* will be analyzed as it illustrates the principles presented above in a larger-scale application.

185. Yogiaman et al., "Knitted Bio-Material Assembly." 58

186. Ibid. 59



Fig. 3.3.3 A photograph of Yogiaman's *Knitted Mycelium Composite Structure.*



Fig. 3.3.4. *The Living Room*, another project by Scott and her team.

Overview: BioKnit

The *BioKnit* prototype, standing 1.8 meters tall and 2 meters in diameter, represents the largest branching dome mycelium-based composite structure utilizing textiles and knitted formwork, enabling the structure to be grown as a single piece shown in figure 3.3.5.[187] A team of researchers and designers from Newcastle University and Northumbria University, the Living Textiles Research group at the Hub for Biotechnology in the Built Environment (HBBE), explored the intersection of biohybrid systems and architecture with a primary focus on the development and application of 3D knitted fabrics with the incorporation of mycelium and bacterial cellulose. Led by Dr. Jane Scott, the team's *BioKnit* prototype integrates mycelium composites into structural applications. The prototype showcases a creative approach in bringing biotechnology, digital fabrication, and computation together to produce a monolithic free-standing biohybrid structure that consists of living mycelium, bacterial cellulose, and fabric textiles.[188]

BioKnit demonstrates how the fabric as a flexible formwork for mycelium can achieve tall, freestanding, large-scale structures.[189] As seen in figure 3.3.7, the research emphasizes the versatility of 3D knitting to produce complex shapes and its biological compatibility with biomaterials such as mycelium and bacterial cellulose. By testing multiple prototypes, BioKnit investigates the potential to form biohybrid materials that could address challenges that current architectural bio-fabrication faces.[200]

187. Biala and Ostermann, "Mycostructures—Growth-Driven Fabrication Processes for Architectural Elements from Mycelium Composites." 512

188. "BioKNIT: Strategies for Living Textile Architectures," Elise Elsacker, accessed December 4, 2023, https://www.eliseelsacker.com/research/bioknit-strategies-for-living-textile-architectures.

189. Romy Kaiser et al., "BioKnit: Development of Mycelium Paste for Use with Permanent Textile Formwork," Frontiers in Bioengineering and Biotechnology 11 (2023): 3, https://doi.org/10.3389/fbioe.2023.1229693.

190. Hoenerloh, Ozkan, and Scott, "Multi-Organism Composites." 10



Fig. 3.3.5 The overall free-standing structure photograph of *BioKnit*.





Fig. 3.3.6 Photographs of biocompatibility between mycelium and bacterial cellulose.

Design and Process

While current research focuses on optimizing the growth and performance of individual organisms for design and construction applications, BioKnit stands out from the projects above as it explores the compatibility of multiple biological or non-biological material systems.[191] A few questions that the study aims to investigate are: 1) how two organisms growth and influence each other, 2) what is the potential of a knit scaffold as a technique to assemble multiple living materials through growth, and lastly 3) how can the challenge of contamination due to varying growth requirements be addressed?[192]

The structure, composed of seven 3D knitted modules filled with inoculated substrate mixture, was assembled by hand into a single preform, a preliminary shaped framework assembled before the final outcome, which facilitated the growth of mycelium into a stable architectural form (see figure 3.3.7).[193] The knitted fabric made from wool and linen, acts as a scaffold that guides, enhances, and restricts the organisms that grow or attach to it. Mycelium in its composite form, acts as a bulk material that provides the necessary compressive strength. Additionally, the overall design of the prototype focuses on the collaborative growing methods between mycelium and bacterial cellulose within a knitted textile framework.[194] The bacterial cellulose, used as a surface treatment and self-adhering skin, adds another layer of complexity and functionality to the structure, supporting 2-metre-long bacterial cellulose pre-grown panels.[195] Another aspect of the project is its exploration of the benefits of mycrocrete, a specialized mycelium paste designed for textile formwork projects in large-scale applications, specifically applied using an injection system.[196] With the recent exploration of woven structures such as 3D Kagome weaving processes and fabric formwork, the team proceeded to 3D knitting which could modify structures within one fabric.[197]

191. Ibid. 1

192. Ibid. 2

193. Kaiser et al., “BioKnit.” 3

194. “BioKNIT.”

195. Hoenerloh, Ozkan, and Scott, “Multi-Organism Composites.” 2

196. Kaiser et al., “BioKnit.” 3

197. Ibid. 3



Fig. 3.3.7 The design team constructing the support in which *BioKnit* hangs on to.

Fungal Species. As opposed to other projects doing tests with various fungal strains, the *BioKnit* prototype only worked with *Ganoderma Lucidum* from start to finish from a local source in the United Kingdom, Urban Farm-It.[198]

Substrate Mixture. A primary aim of the tests was to determine the properties of the proposed mycrocrete mixture within a permanent textile formwork. As shown in figure 3.3.8, material testing of mycrocrete without textile or mycelium inoculation was conducted for comparison to elucidate the impact of textile formwork and mycelium on the mechanical properties of the chosen BioKnit materials.[199] The proposed mycocrete paste consists of beechwood sawdust soaked in water, pre-inoculated with 2% of mycelium spawn, before adding in the additives of paper powder, paper fibre clumps, water, glycerin, and xanthan gum.[200]

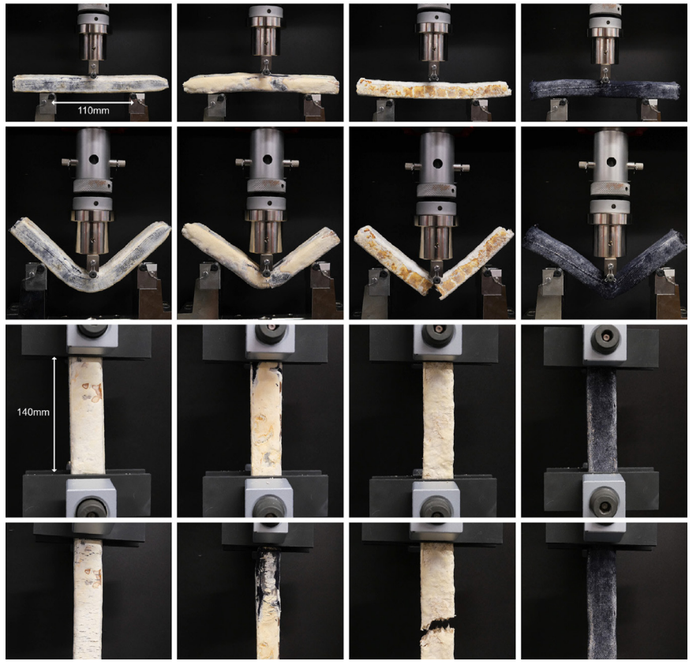


Fig. 3.3.8. Series of images showing the mechanical strength of mycelium.

198. Ibid. 4

199. Ibid. 3

200. Ibid. 5

201. Agraviador et al., "Computation and Material Investigation in the Design of Biohybrid Textiles towards Architectural Integration." 3

202. Ibid. 7

203. "BioKNIT."

Base/Formwork Components. The transformative process of knit programming for the project is a key conceptual tool for developing biohybrid systems where biomaterials evolve through multiple states of flexibility and rigidity, wet and dry, living and non-living.[201] To grow the prototype, three major components were required; the mycrocrete paste, the assembled knit formwork, and an external framework that served as a growing chamber and integrated hanging system (see figure 3.3.9). The knitted modules were sewn together on-site with polyester thread, leaving gaps for inoculated substrate injection, to ensure consistent, tightly packed mycelium substrate throughout the structure (see figure 3.3.10).[202]



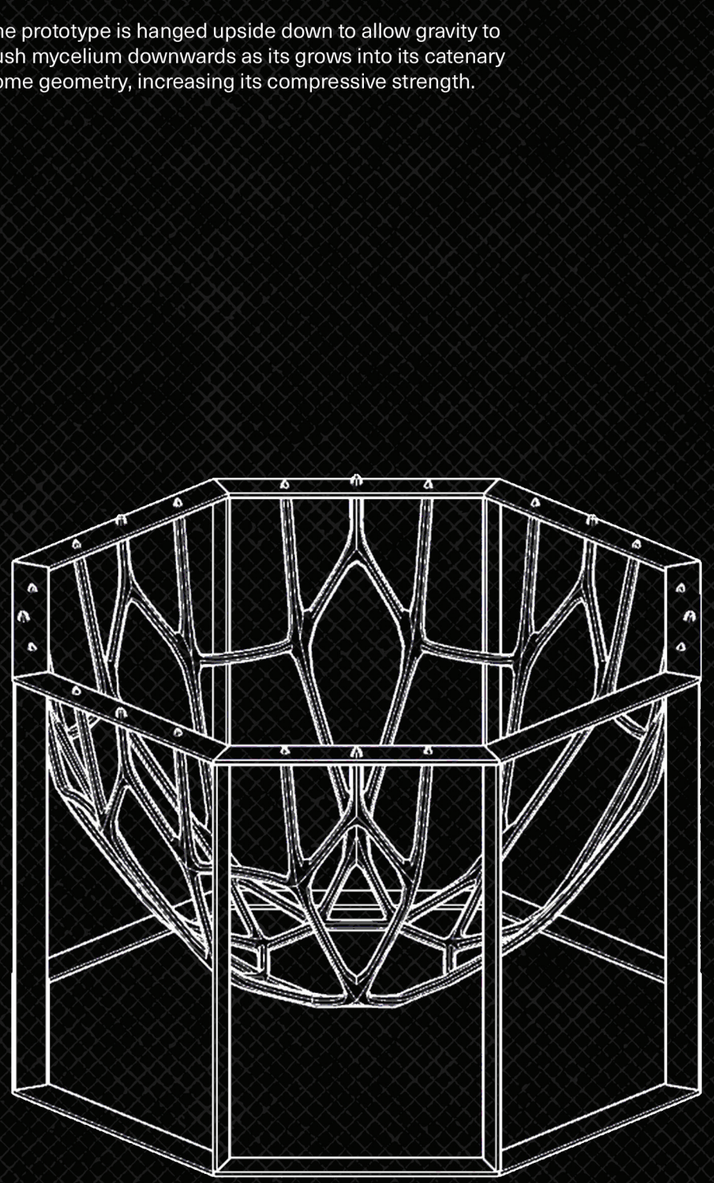
Fig. 3.3.9 (next page). Diagram of the growth process of the *BioKnit* prototype.

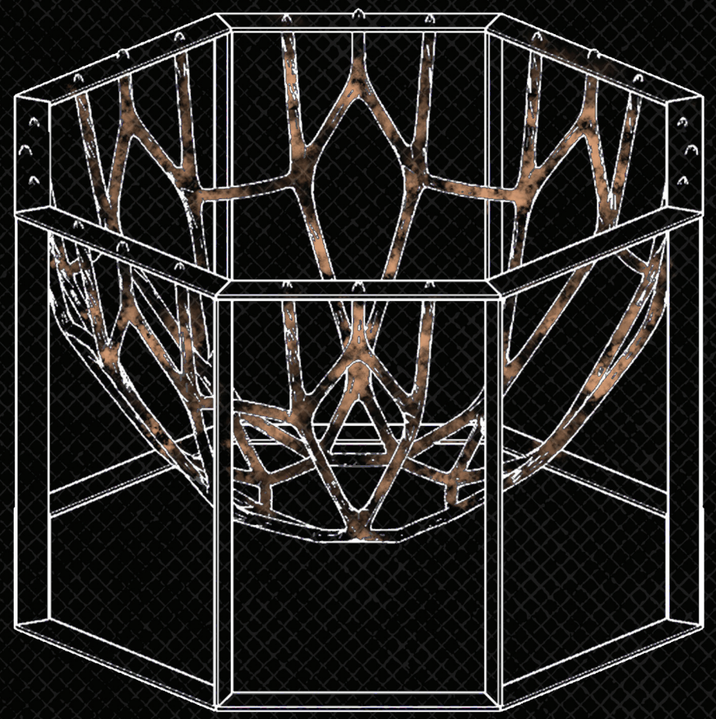
Fig. 3.3.10. Series of images showing the step by step procedure of filling the knitted hollow cores with mycocrete.

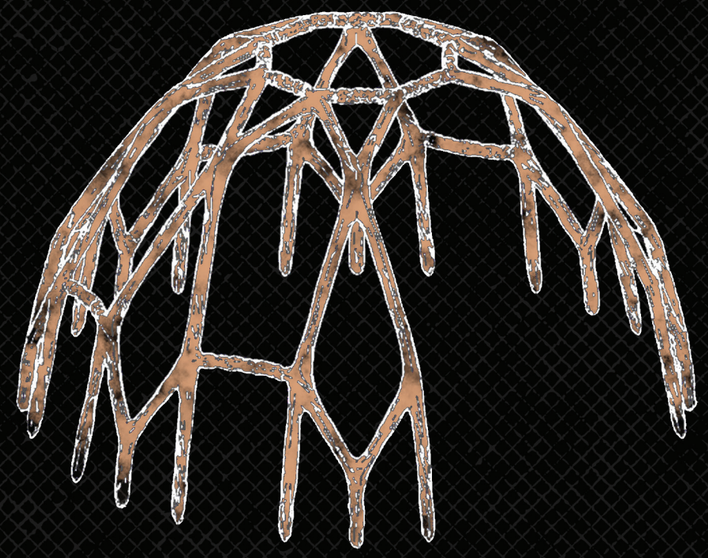
Hardware/Software. The team faced an initial design challenge to create a structural system that could contain and form the mycelium substrate despite the extensibility of knitted fabric. Computational modelling integrated with knit programming allowed the exploration of parametrically defined geometries and created branching preforms using Grasshopper and Kangaroo2 plugins. The tools allowed for variation in material properties, physics simulations, and refinement of the knit structure prior to fabrication.[203]

SELF-SUPPORTING

The prototype is hanged upside down to allow gravity to push mycelium downwards as its grows into its catenary dome geometry, increasing its compressive strength.







After 22 days, once mycelium has overgrown its base knitted formwork, it is turned 180 degrees to allow the structure to stand freely, without the need of external supporting structures.

Assembly Technique and Labour. The system devised for filling the tubes involved a manually filled injection gun with a 17 mm nozzle. The gun, filled with mycocrete paste, was inserted into the tubular fabric at several filling points. The fabric was gathered up around the nozzle and filled at a consistent rate, with the gun being pulled back to allow the fabric to expand with the mycocrete paste. After the filling was done, the seams were hand-sewn to close each filling point.[204] The curvature of the vault shown in figure 3.3.11, is achieved by exploiting the textile's behaviour in tension by hanging the assembled structure in a soft state, forming a catenary hammock prior to consolidation through mycelium growth.[205] As a secondary process, the panels grown from bacterial cellulose shown in figure 3.3.12 of approximately 200 cm x 50 cm, were applied to the BioKnit structure to form a skin over two knitted modules. Once applied and dehydrated over five days, the panels adhered to the textile where it also contained mycelial colonization but resisted adhesion to the surface of the fabric alone.[206]



204. Kaiser et al., "BioKnit." 9

205. "BioKNIT."

206. Agraviador et al., "Computation and Material Investigation in the Design of Biohybrid Textiles towards Architectural Integration." 8

Fig. 3.3.11 (left) A photograph of the catenary dome turned upside down to during growth period.

Fig. 3.3.12 (right) A zoomed in photograph of how bacterial cellulose skin adheres to the mycelium textile formwork





207. Ibid. 6-7

208. Kaiser et al., “BioKnit.” 4

209. Agraviador et al., “Computation and Material Investigation in the Design of Biohybrid Textiles towards Architectural Integration.” 8

Growth Process. Once fabrication was completed, the growth chamber was wrapped in thermal foil to maintain humidity and the required temperature for ten days. During its growth, the mycelial hypha colonized through the substrate mixture and penetrated through its knitted fabric support, consuming the nutrients provided and binding the materials all in one single structure (see figure 3.3.13 and 3.3.14).[207] For optimal mycelium growth, the environmental conditions include a temperature of 21-28 degrees Celsius, with relative humidity of 50-60 degrees in complete darkness.[208]

Post Treatment. After two weeks, the foil was removed and the structure was left to air dry for 22 days, achieving a stiff and solid structural property.[209] The final fabrication step involved rotating the structure 180 degrees to form the catenary vault. Despite the concerns that the structure would not be able to withstand the bending forces, the combination of mycelium’s compressive strength and tensile strength of the fabric ensured its stability.

Fig. 3.3.13 (left) A zoomed in photograph of mycelium penetrating through the gaps in the textile formwork.

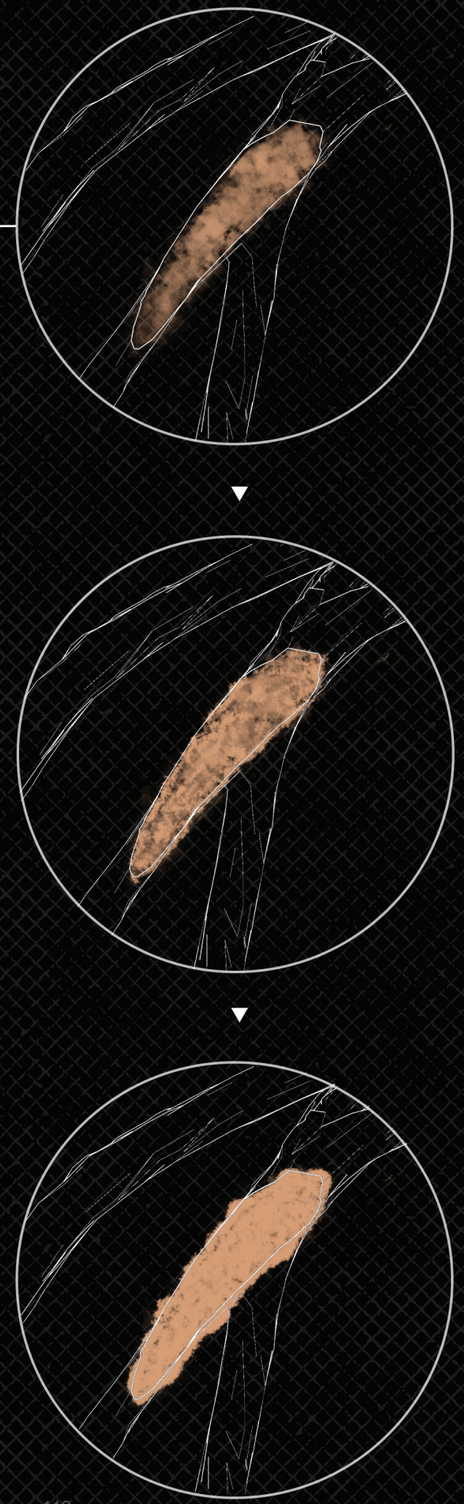
Fig. 3.3.14 (next page) A diagram showing the overgrowth of mycelium on the knitted skin.

KNITTED SCAFFOLD

The self-supporting prototype demonstrates how mycelium is capable of colonizing and overgrowing its base formwork from the inoculated, injected mycocrete mixture, resulting in an integral, lost, knitted scaffold.

Raising concerns in previous mycelium-based projects, the project *BioKnit,* resulted in a zero-waste formwork structure as the growth of mycelium becomes one with its base. The diagram illustrates mycelium penetrating through the holes of its knitted textiles, concealing the woven material as it continues to grow.





Reflection: Bio Hybridization as part of "The Living"

The *BioKnit* prototype could be viewed as an embodiment of a textile's lightweight flexibility, resulting in a self-supporting structure through the rigidity of mycelium composite and the structural efficiency of catenary geometry. Unlike the traditional methods that involve growing mycelium components in moulds and assembling them into larger structures, *BioKnit* demonstrated the challenges and benefits of cultivating a continuous mycelium structure.

Biological Utilization: Myco-Textile Colonization

Compared to current bio-fabrication research that focuses on optimizing individual growth and organism performance, *BioKnit* demonstrates a new approach to utilizing other components to co-exist and enhance the biological capabilities of mycelium. Through experimenting with living mycelium, the team discovered unique findings that revealed collaborative symbiotic systems, which would not have been possible with conventional dried mycelium. For instance, the research unveiled the presence of mushrooms from mycelium that increased bacterial cellulose formation around those areas, suggesting an enhanced nutrition supply. Furthermore, the successful mycelial growth on the textile surface and colonization of the bacterial cellulose prove that these organisms can establish a symbiotic relationship that could be applied in today's architecture and construction industry.

BioKnit also addresses the challenges of using soft, extensible knitted fabrics incorporated with mycelium-based paste and demonstrates the effective collaboration between mycelium, textiles, and bacterial cellulose. *BioKnit* displays the potential of using textile knit scaffolding to assemble multiple living composites through the self-growth capability of mycelium to colonize its base and transform the materials into a coherent whole. Additionally, the tools and techniques applied in the project allowed for efficient tuning and structure refinement of material properties, a factor that is often not utilized enough in most nonliving projects. Despite the project's success structurally, several challenges remain, particularly concerning contamination during its growth phase. The increased humidity and presence of sugar from the bacterial cellulose resulted in favourable conditions for unwanted organisms to grow, highlighting the need for optimized environmental conditions and systems for humidity and ventilation control.[210] To further advance the project, the team is developing strategies to ensure the resilience of the material and the structure outside a controlled environment for viable in-situ construction applications.

210. Hoenerloh, Ozkan, and Scott, "Multi-Organism Composites." 9-10

211. Yogiaman et al., "Knitted Bio-Material Assembly." 63

212. Kaiser et al., "BioKnit."11

213. Ibid. 10

214. Hoenerloh, Ozkan, and Scott, "Multi-Organism Composites." 10

215. Scott, Jane (research and design lead). "Email to Nixon Garcia". June 28, 2024.

Integral & Lost Formwork: Knitted Scaffold

As previously mentioned, a key aspect of the project is its use of knitted textile scaffolds that serve as structural formwork for the inoculated mycelium substrate, or mycocrete. To address the wasteful formwork associated with myco-fabrication of nonliving mycelium-based composite projects, *BioKnit* incorporates the knitted scaffold as an integral component of the structure. The textile scaffold shapes and supports the premature mycocrete paste and allows mycelium to overgrow and conceal the formwork during its colonization process. As a result, one of the most significant findings from the project is the prototype's structurally improved performance. The prototype features a unique catenary geometry dome that exhibits the sufficient compressive strength of mycelium-knit composites to support a free-standing, slender vault.

Based on the reflections from *BioKnit* and previous knitted projects, there is an assumption that the increased density of nutrient-rich textiles results in an increase of hyphae growth, strengthening the bond between the body of the composite and the knitted skin for an increase in overall structural performance. The fungal colonization on the bacterial cellulose and textile skins also showed enhanced structural reports compared to the parts without mycelium growth.[211] Mechanical testing showed a dramatic increase in tensile, compressive, and flexural strength that utilized the biohybrid collaboration of the materials in comparison to conventional sawdust substrates without textile formwork.[212] Moreover, the approach could be a reference to how future construction can exploit textile's lightweight formability and the structural efficiency of catenary geometry.[213]

Material Understanding & Visual Acceptance: Imperfections

The *BioKnit* prototype highlights the unique biohybrid interaction between mycelium and bacterial cellulose (BC), demonstrating that the organisms could effectively grow together (see figure 3.3.15). However, the growth of BC was influenced by the growth requirements of mycelium, leading to uneven growth. The presence of fruiting bodies growing from the mycelium increased BC formation around that area, suggesting a localized increase in nutrition supply for the cellulose.[214] After having a better understanding of the material behaviours, Scott responded by growing the materials separately and applied the BC panels to the structure only after the mycelium dried. The panels adhered well to the mycelium/textile composite but not to fabric alone, indicating that the process succeeded by having two organisms collaborate.[215]

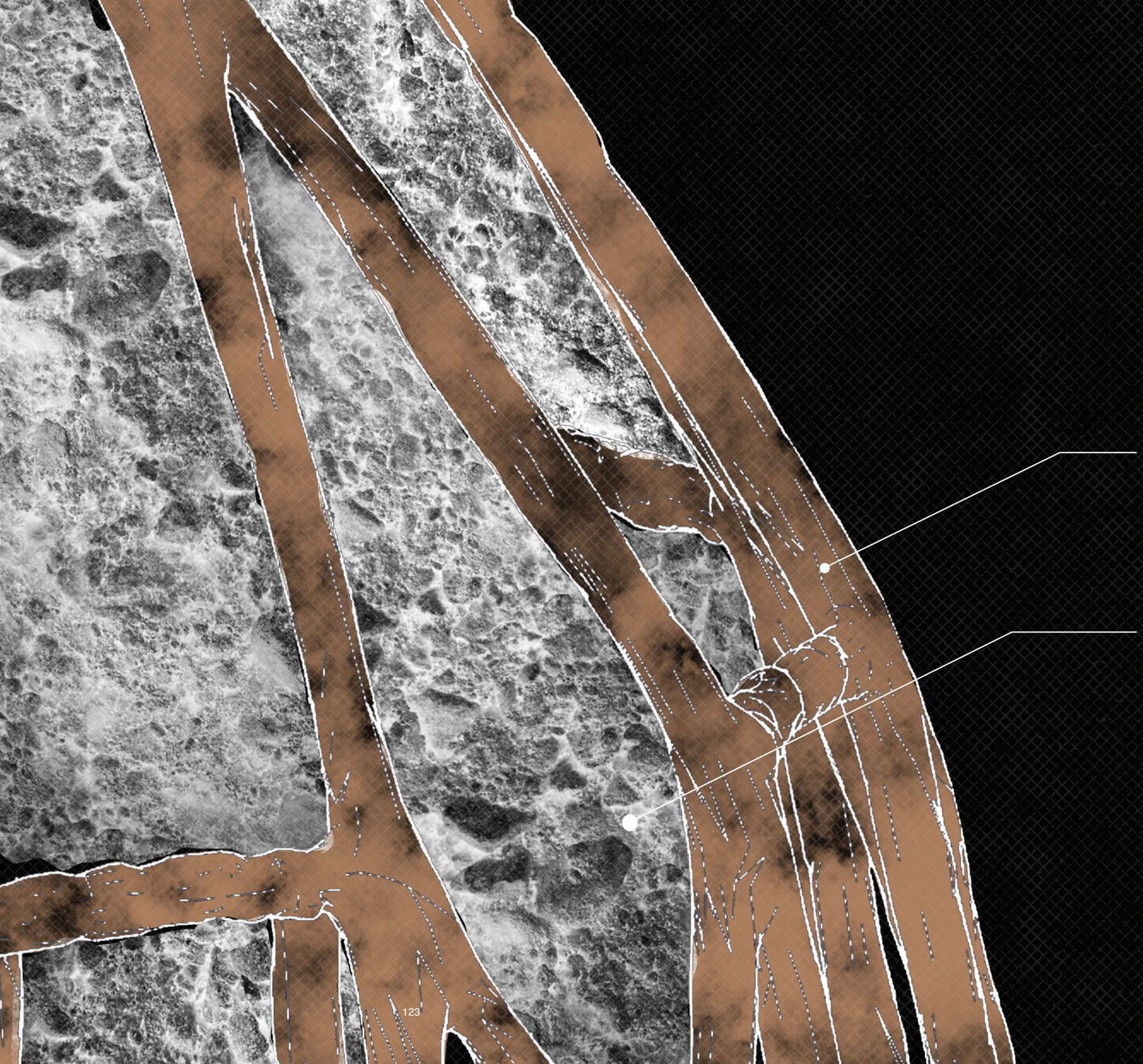
Moreover, the HBBE design team seeks to answer is whether multi-microbial systems can produce durable structures made from biomaterials whilst transforming the look and feel of materials for architecture. Although the visual appearance of the collaborative prototype involving textiles, mycelium, and bacterial cellulose was not the primary focus, it is evident that the team chose not to conceal the natural imperfections of mycelium and bacterial cellulose. Furthermore, no finishing touches were applied to the final product, showcasing the organic and natural aesthetics of the organisms' patterns and textures. Additionally, in comparison to previous conventional projects of nonliving mycelium works that aim to visually present their project as free-standing and self-supporting through hidden formworks, *BioKnit* harnessed the colonizing processes of living mycelium to incorporate its organic formwork to be an integral component of the monolithic, free-standing structure.

Fig. 3.3.15. A diagram showing the biocompatibility of mycelium and bacterial cellulose.

BIOHYBRIDITY

The project highlights the unique biohybrid interaction from biomaterials, mycelium and bacterial cellulose. The compatibility of both growing materials was seen to be successful after numerous findings of higher mycelium growth in areas where both materials meet. There are also limitations in the current state of the project as bacterial cellulose wouldn't adhere directly to the mycelial surface.

The project also showcased the natural aesthetics offered by both bacterial cellulose and mycelium, advocating for both visual acceptance and natural imperfections of biomaterials



3.4 The Bio-Tectonic of Living Mycelium: *Mycelium Tectonics*

Introduction: Bio-Tectonic

The perception of the environment has dramatically changed over the last 20 years, leading to new and deeper sensitivities. The study of Earth, for example, has significantly increased people's awareness of climatic and tectonic dynamics, and the fragile balance of natural processes on the planet.[216] With technological advancements and the inventions of tools such as the electron microscope, material understanding has shifted from assumptions regarding the monolithic nature of the material to recognizing them as micro-fibrous assemblages.[217] Moreover, new representation and simulation techniques are constantly being developed to establish a better understanding of self-organization and growth processes of the organisms, and their corresponding influential external factors.[218] As shown in figure 3.4.1, parametric models which have become increasingly apparent in contemporary architecture are characterized by linear relationships between parameters and geometric transformations. Despite the evolution, parameters limit the model to a set of fixed boundaries embedded in the initial conditions of the system, preventing the exploration of innovative possibilities found in natural growth and development processes.[219] In contrast, shifting from the conventional designing approach challenges the behavioral systems and hierarchies embedded in the today's design processes. By doing so, these non-linear design strategies have radical implications for the development of architectural form, structure, and tectonics.[220]

Tectonics, in its architectural context, is the principle of material honesty – material usage in ways that respect their innate properties.[221] It is the attempt to link construction, structural, and functional order to the realm of art, which may include symbolic, decorative and aesthetic elements. However, to fully understand tectonics in architecture and construction, it is necessary to view it as a relationship between the mechanisms and processes, the art of building assembly (see figure 3.4.2).[222] Biological systems, in this context, offer insight into the concept of relationships between structures and aesthetics, functionality, and form.[223]

216. Gianluca Tabellini et al., "Prof. Alessio Erioli Prof. Alessandra Zambonelli Maurizio Montalti Philip Ross," 15

217. Roland Snooks, "Fibrous Assemblages and Behavioral Composites," in The Funambulist Papers, Volume 1, ed. Léopold Lambert (Punctum Books, 2013), 3, https://doi.org/10.2307/jj.2353910.32.

218. Tabellini et al., "Prof. Alessio Erioli Prof. Alessandra Zambonelli Maurizio Montalti Philip Ross." 15

219. Ibid. 19

220. Snooks, "Fibrous Assemblages and Behavioral Composites." 2

221. Tabellini et al., "Prof. Alessio Erioli Prof. Alessandra Zambonelli Maurizio Montalti Philip Ross." 11

222. Ibid. 11

223. Ibid. 12

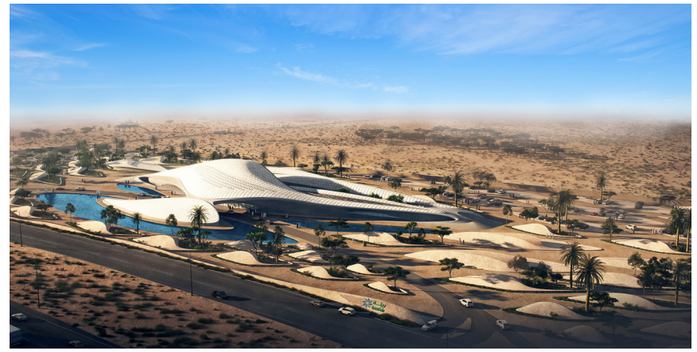


Fig. 3.4.1 An exterior render of a parametric design building.



Fig. 3.4.2 The art of construction process of a building.

A radical interdisciplinary approach is essential where technology is seen as interconnected ecological systems rather than isolated. By embedding technology deeply into architectural practice, a stronger relationship between functional and decorative features can be established.[224] In search of this kind of work in the field, Tom Wiscombe and his team designed prototypes like the *Batwing* shown in figure 3.4.3, that challenge standardized fixtures by integrating structural, mechanical, lighting, and enclosure systems into a single, operating structure. The systems incorporated in the model were fused in a manner that they become spatial and atmospheric.[225]

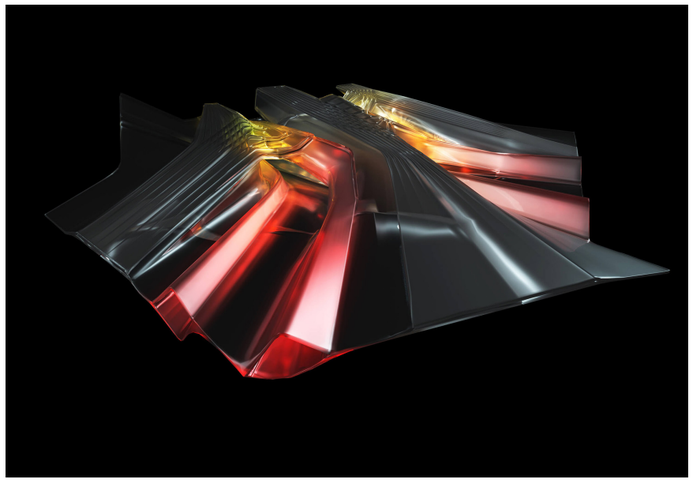


Fig. 3.4.3 The prototype, *Batwing*, by Tom Wiscombe.

A project that exemplifies modelling biological behaviors influenced by their respective environments is the work carried out by Przemyslaw Prusinkiewicz at the University of Calgary by using algorithms to simulate plant growth, leading to environmentally adaptive designs.[226] Moreover, there has been increased attention in the mathematical modelling of hyphal branching that seek to explore the collective attributes of mycelium, rather than individual hyphae growth.[227] For example, the *Neighbour-Sensing* model (figure 3.4.4) by Meskauskaus et al. predicts three-dimensional fungal growth patterns as well as simulation of complex fruiting body shapes. Other works within this specific approach of biological modelling include Regalado et al.

224. Tom Wiscombe, "Beyond Assemblies: System Convergence and Multi-Materiality," Bioinspiration & Biomimetics 7, no. 1 (February 2012): 3, https://doi.org/10.1088/1748-3182/7/1/015001.

225. Wiscombe, "Beyond Assemblies." 3

226. Tabellini et al., "Prof. Alessio Erioli Prof. Alessandra Zambonelli Maurizio Montalti Philip Ross." 16

227. A. Meskauskas, M.D. Fricker, and D. Moore, "Simulating Colonial Growth of Fungi with the Neighbour-Sensing Model of Hyphal Growth," Mycological Research 108, no. 11 (2004): 1242, https://doi.org/10.1017/S0953756204001261.

228. Meskauskas, Fricker, and Moore, "Simulating Colonial Growth of Fungi with the Neighbour-Sensing Model of Hyphal Growth." 1242

229. Ibid. 1242

230. Tabellini et al., "Prof. Alessio Erioli Prof. Alessandra Zambonelli Maurizio Montalti Philip Ross." 17

combined nutrient depletion models with reaction-diffusion systems to simulate mycelial structures that respond to nutrient changes.[228] Ermentrout and Edelstein-Keshet built cellular automaton models that incorporate growth, branching, death, and nutrient uptake.[229] These models not only assists in improving visualization processes of mycelium but also emphasizes the potential contribution of the tools' specific configurations and characteristics of the to rethink design approach by following self-organization principles.[230] Inspired by the methodologies laid out by similar projects mentioned above, *Mycelium Tectonics* integrates multiple systems that blend architecture with technology and biology, making it a compelling project to explore within the context of modelling biological exploration.

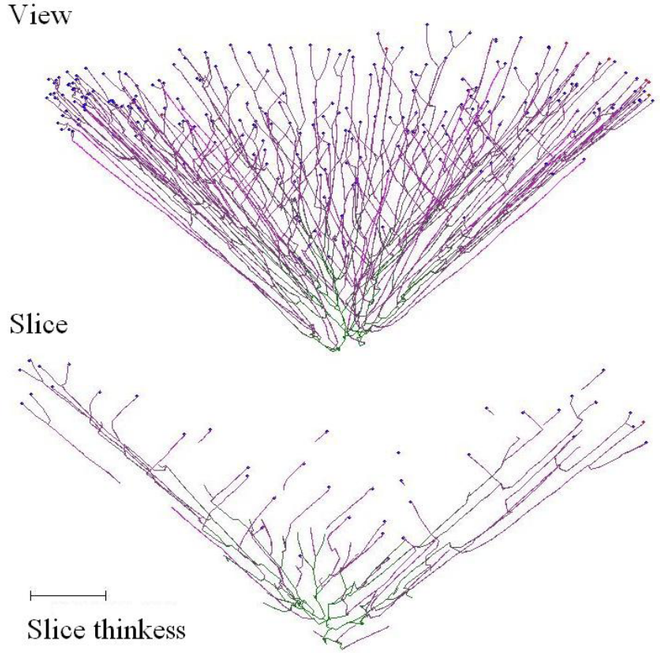


Fig. 3.4.4. The *Neigbour-Sensing* model by Meskauskaus *et. al.*

Overview: Mycelium Tectonics

Conducted as a thesis project by Gianluca Tabellini at the University of Bologna, *Mycelium Tectonics* is a multidisciplinary research project that connects spatial organization with internal mechanisms facilitated by the living hyphal networks of mycelium (see figure 3.4.5).[231] The work primarily focuses on fungi's self-organization and intelligence to describe a new kind of tectonics.[232] The project illustrates how architectural design can integrate technological advancements and biological processes to innovate both in form and function, by modelling architectural topology through the growing of mycelium on three-dimensional hemp-fiber scaffolds.[233]

Since tectonics relates the processes of constructing matter with the resulting morphology, Tabellini was intrigued by guiding the mycelium to "process" a designed space, allowing the material to shape and adapt within those predetermined parameters.[234] *The Living Fiber* shown in figure 3.4.6, a composite system fabricated in the thesis M*ycelium Tectonics*, consists of multiple plexiglass plates supporting the heterogeneous, three-dimensional substrate of hemp fibers that will act as a primary base for growing mycelium. The cylindrical prototype measures 18 cm in diameter and approximately 35 cm in height.[235]



231. Campbell et al., "Modular Mycelia." 4

232. "Mycelium Tectonics – Materiability."

233. Noam Attias et al., "Implementing Bio-Design Tools to Develop Mycelium-Based Products," The Design Journal 22, no. sup1 (April 1, 2019): 2, https://doi.org/10.1080/14606925.2019.1594997.

234. Tabellini et al., "Prof. Alessio Erioli Prof. Alessandra Zambonelli Maurizio Montalti Philip Ross." 51

235. Ibid. 119

Fig. 3.4.5 *The Living Fibre* prototype before mycelium inoculation.

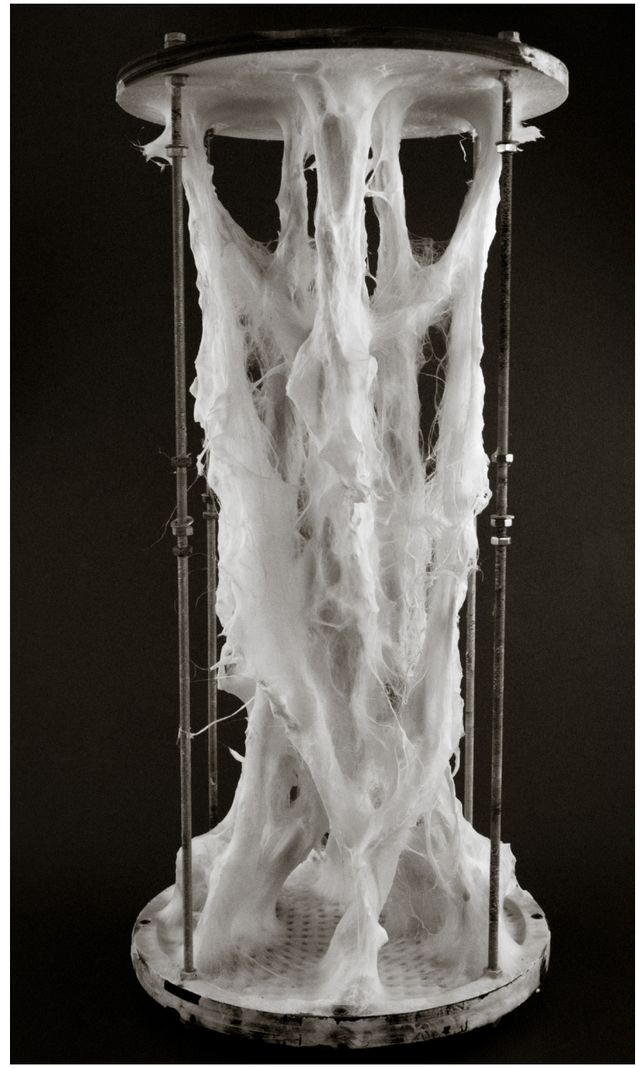


Fig. 3.4.6 *The Living Fibre* prototype after mycelium colonization on the fibrous base.

Design and Process

The cylindrical prototype that bounds the space where the operations occur draws inspiration from the vertical systems of the Greek columns, famous for their structural and decorative features (see figure 3.4.7). However, the tectonics explored in this project aims to rethink architectural hierarchies from a differentiation perspective rather than treating ornaments as subordinate to structure. Inspired by the principles laid out by Frei Otto, his experiments expressed tectonics through the spatial organization of wool, combining structural and aesthetic elements in a single continuous system.[236] Furthermore, the strategies implemented during the simulation and growth process have been emphasized throughout the research. *The Living Fiber* prototypes were initially digitally simulated, then tested using small glass dishes shown in figure 3.4.8 and analyzed to build physical models for controlled mycelium growth.[237]







Fig. 3.4.7 (left) A free standing sample from *Mycelium Tectonics* inspired by the Greek columns.

Fig. 3.4.8 (right) Petri dish experiments, prior to fabrication of the *Living Fibre* prototype.

236. Ibid. 119

237. Ibid. 5

238. Ibid. 87

239. Ibid. 133

Formwork Components. The hypothesis of using a hemp-based fibre-composite system emerged from the advantages of working with a material that not only supplies the necessary nutrients for mycelial growth but also offers an initial three-dimensional structure.[238] The formwork system is an arrangement of hierarchized hemp families with differing volumes and densities. As shown in figure 3.4.9, the order starts with the hemp cable category, which consists of frayed hemp bundled to approximately 10 mm in diameter. Although the fibres tend to align in one direction, the high indeterminacy results in a heterogeneous system at a micro-scale. Followed by the hemp wall, the second order takes advantage of the versatility of the frayed hemp by arranging the materials in varying lengths to form surfaces that depend on the behaviour and flexural characteristics of the material. Lastly, the hemp mix combines the bundle system at the top and bottom of the model. This element acts as a binding component whose density will vary depending on the interactions of all three hemp categories.[238]

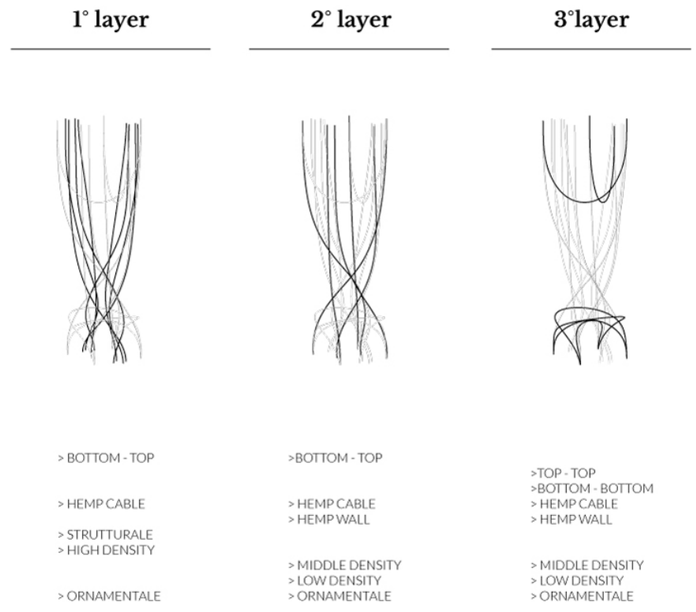


Fig. 3.4.9 A diagram showing the hierarchy of the fibrous base system.

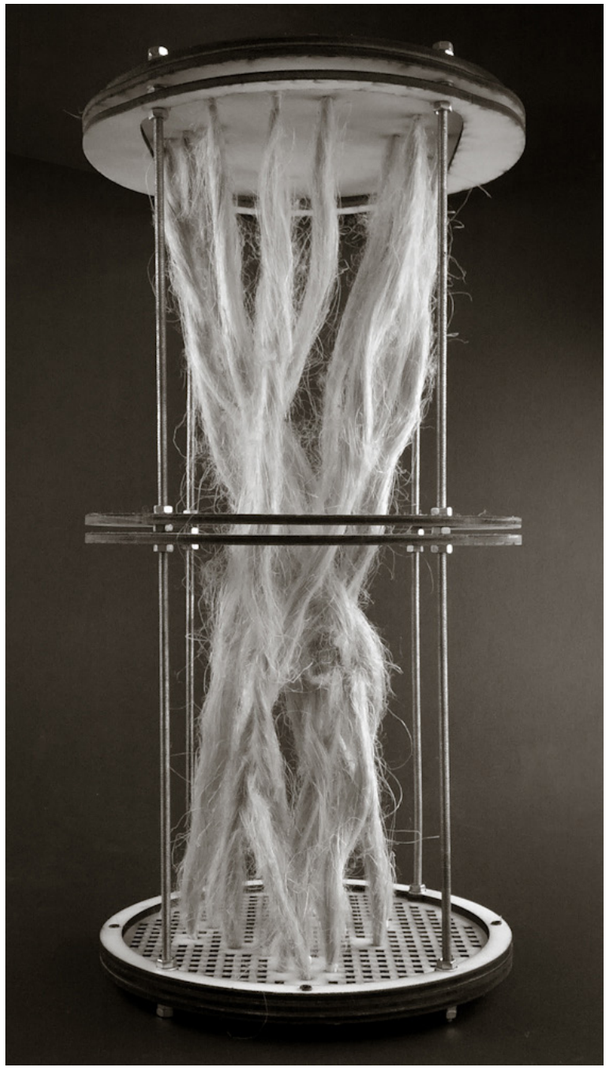


Fig. 3.4.10 The fibrous system used as a guiding formwork for the prototype.

240. Ibid. 74

241. Ibid. 94

242. Ibid. 102

243. Ibid. 146

Hardware and Software. Processing was the primary software used for the experimentation and digital exploration of new systems that relate objects through codified rules and behaviors. The study conducted in *Mycelium Tectonics* involved an understanding of agent and flocking systems in architecture through growth and morphogenesis simulations. Through digital programming, each hypha can be viewed as a single agent capable of branching and exploring available space depending on the availability of nutrients and the presence of neighboring agents.[240]

In terms of the hardware used for the prototypes, three different preliminary tests were conducted by arranging hemp bundles vertically with laser-cut wooden plates for more precise control of fiber arrangement (see figure 3.4.11).[241] The first model is a result of various configurations influenced by the results from the smaller-scale experiments with a high emphasis on the prototype's aesthetic values.[242] While for the final *Living Fiber* prototype, two coupled discs were used to secure the hemp wall placed at the top, punctured with holes to allow multiple rope hemp to pass through (see figure 3.4.10). As shown in figure 3.4.12, water-soaked cotton was inserted at these openings to ensure humidity during the mycelium growth process. As the primary support of all the components, four threaded bars with nuts formed the structure, with the base consisting of a 4 mm triple-layer poplar, also provided with circular and rectangular holes for hemp passage and humidity transfer.[243]

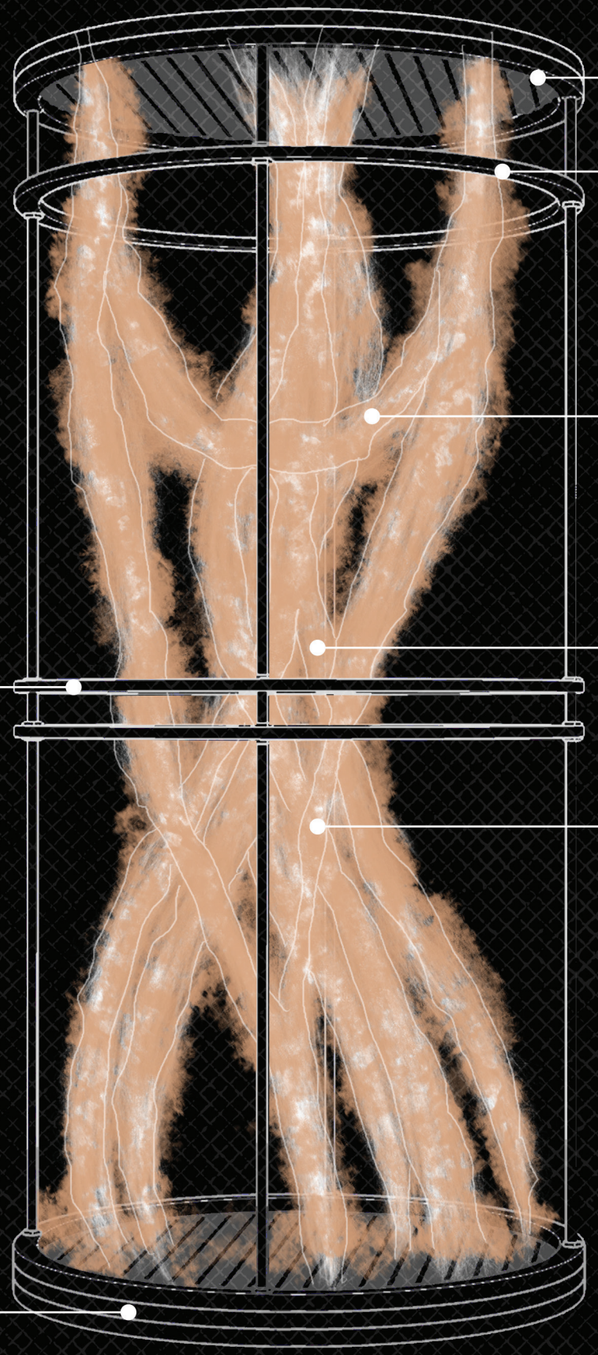
Fig. 3.4.11 (next page) A diagram of the *Living Fibre* components.

Fig. 3.4.12 (right) A photograph of the cotton balls soaked in water for humidity.



MACHINIC

Although the prototype was self-supporting later on, the project demonstrated the influence of external factors in the growth and behaviour of mycelium. Mycelium Tectonics took advantage of the advancement in tools to ensure proper growth and avoid contamination during its growth period.



Growth Process. Five grains of wheat inoculated by *Pleurotus ostreatus* are spread on the fibres in a sterile environment under a laminar flow hood to initiate the growth process.[244] Once the hemp system and the cotton balls are secured in the cylindrical model, the prototype is wrapped in plastic to maintain the suitable moisture level required for mycelium growth (see figure 3.4.13).[245] The growth occurs in complete darkness at a constant temperature of 22.5 degrees Celsius over twelve days.[246] It was also observed that the mycelium network growth and connections consistently occurred in the model's central part, where the hemp fibres were densest and intertwined the most, resulting in a distinctive material composition.[247] As shown in figure 3.4.14, the colonization of mycelium networks through the hemp fibres, the hanging strands transform into self-supporting structural elements, and the supporting rods get removed (see figure 3.4.15).[248] Moreover, the addition of multiple supporting hemp systems results in a diverse aesthetic outcome, as the organization of the material varies based on the starting and ending points of the fibers(see figure 3.4.16).[249]





244. Ibid. 102

245. Campbell et al., "Modular Mycelia." 4

246. Tabellini et al., "Prof. Alessio Erioli Prof. Alessandra Zambonelli Maurizio Montalti Philip Ross." 102

247. Ibid. 102

248. Campbell et al., "Modular Mycelia." 4

249. Tabellini et al., "Prof. Alessio Erioli Prof. Alessandra Zambonelli Maurizio Montalti Philip Ross." 124

Fig. 3.4.13 (left) The prototype wrapped in plastic to ensure proper mycelium growth.

Fig. 3.4.14 (right) Microscopic image of mycelium network bridging the gaps and interlocking with one another.

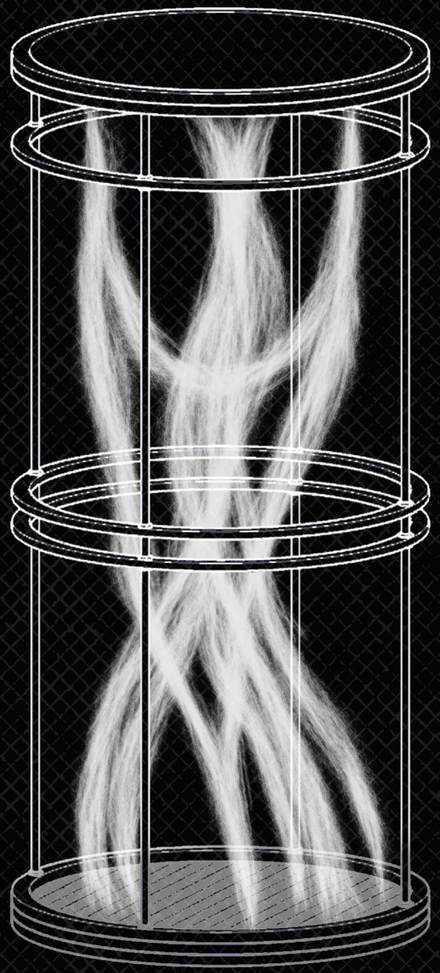
Fig. 3.4.15 (next page) A step by step diagram showing the growth process of the *Living Fibre* prototype.

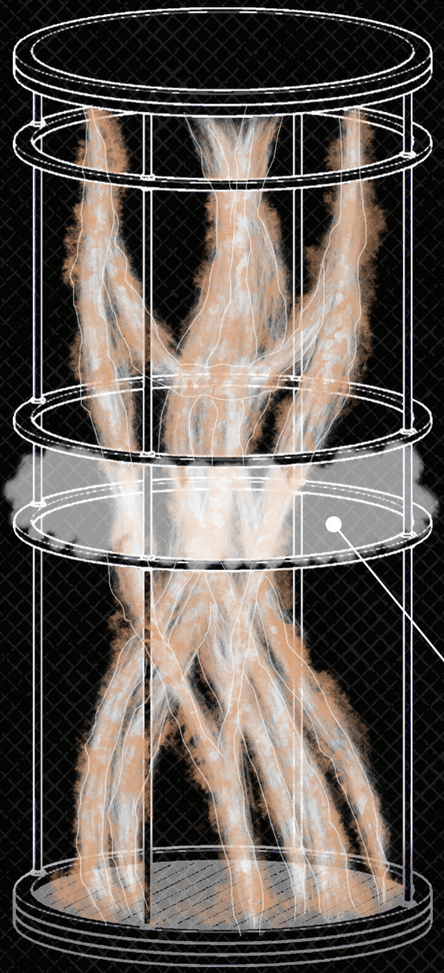


Fig. 3.4.16 A zoomed in photograph showing the various density points after mycelium growth.

BIO-TECTONIC

The project embraces the art in the process of the prototype's growth, referred to as tectonic in the project. The Living Fibre prototype was observed as it started with a fibrous system of hemp fibres, to a self-standing column of mycelium-colonized hemp structure. The supporting components were completely removed by the end of the project period.







Reflection: Bio-Tectonic as part of "The Living"

The dynamic boundaries of living systems define where and how natural selection operates, framing it as an interactive process rather than a mechanical sorting of individual units. These boundaries enable living systems to respond to environmental heterogeneity, which they interact with and generate.[250] Similarly, in computational design, generative algorithms and self-organizing procedures play crucial roles in the exploration of complexity. These algorithms mirror the adaptive characteristics of living systems, offering designers tools to produce responsive designs to varying conditions. However, their relevance remains strictly dependent on the designer's ability to interpret and implement architectural intent.[251]

Biological Utilization: Bio-Tectonic

The prototypes exemplify complex interactions where functionality emerges from self-organization rather than individual components. The project provides a deeper understanding of mycelium's tectonic capabilities, focusing on its unique biological properties of differentiation and adaptation rather than the conventional approach of seeking a homogenous material for predefined forms. The incorporation of living components in construction marks a shift from traditional practices that rely on the physical and chemical properties of nonliving materials. Mycelium's self-organization ability provides insights into the potential of internal mycelial systems in architectural design that adapt to their environment without external regulation.
Additionally, Tabellini draws attention to the advancements in technology that have shifted today's material perspective. Modern simulation techniques, applied in the project, allow for a deeper exploration of biomaterials' self-organization and growth processes influenced by external stimuli. With the simulation of some natural behaviours, designers have framed tectonics in a digital context that opens up the possibility of generating forms that are coherent with the structural and cultural forces at play.

Integral & Lost Formwork: Machinic

Another strategy explored in the project is its leveraging of unique mycelium and fibro-composite systems' properties. Expanding on biological utilization, innovations in connections advance beyond the machinic logic of assembly but rather embrace the biological functions of growth and repair, eliminating the requirements for hardware for a more seamless aesthetic. *The Living Fiber* prototypes utilize a hemp fibre-based composite formwork that serves as a three-dimensional substrate for mycelium growth. Contrary to the traditional purpose of substrates in mycelium-based composite fabrication, the fibro system offers not only an initial structural framework with basic mechanical properties but is also a nutrient source that facilitates the living organism's growth and colonization.

250. A. D. M. Rayner, Z. R. Watkins, and J. R. Beeching, "Self-Integration – an Emerging Concept from the Fungal Mycelium," in The Fungal Colony, ed. N. A. R. Gow, G. D. Robson, and G. M. Gadd, 1st ed. (Cambridge University Press, 1999), 2, https://doi.org/10.1017/CBO9780511549694.002.

251. Tabellini et al., "Prof. Alessio Erioli Prof. Alessandra Zambonelli Maurizio Montalti Philip Ross." 19

252. Ibid. 94

253. Ibid. 158

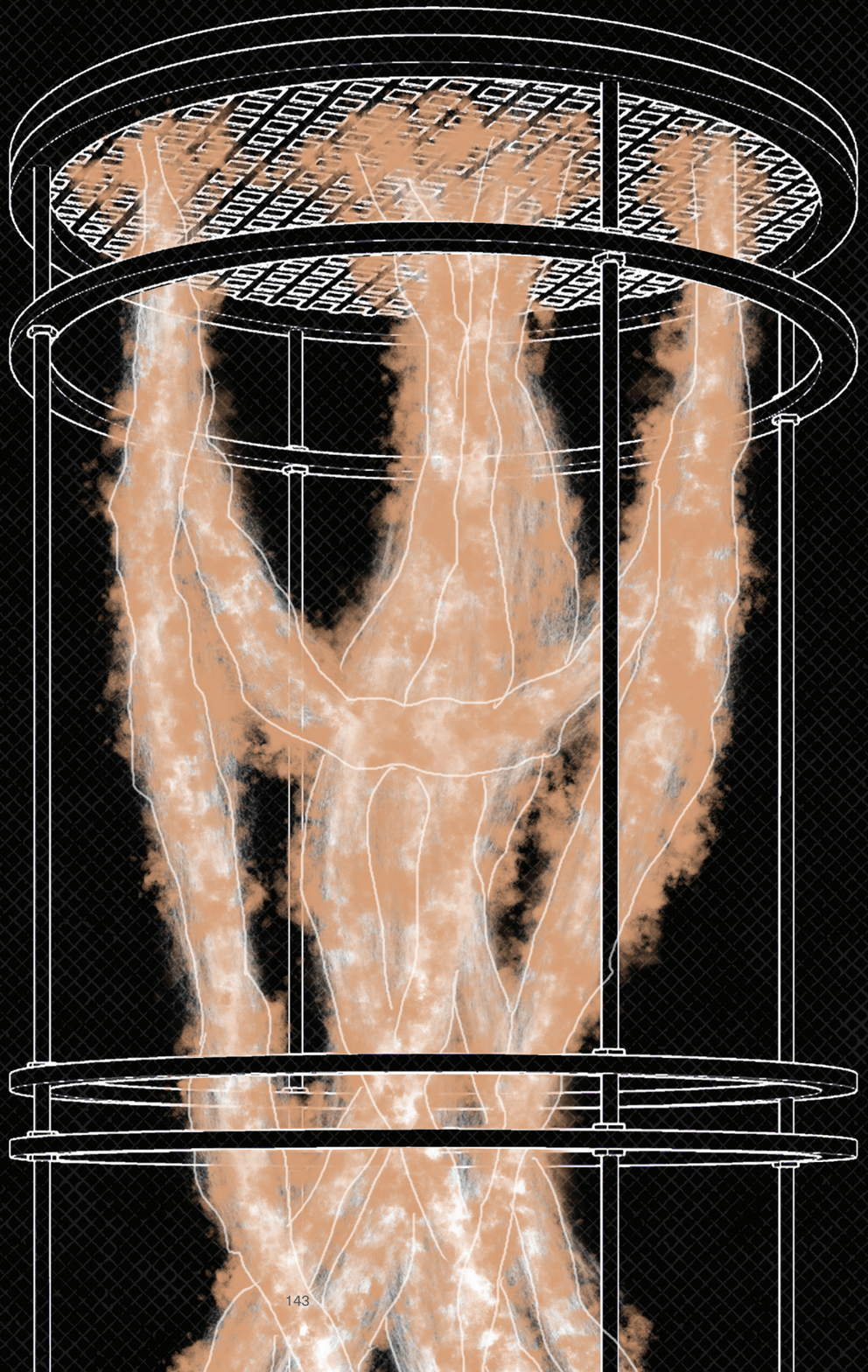
254. Ibid. 159

Fig. 3.4.17 An illustration of the aesthetically chaotic outcome of the prototype.

The exposed layout of the model enables a demonstration of mycelium's structural properties and informs a better understanding of its structural capabilities and gaps. The project visually expressed how gravity and external loads from supporting plates resulted in the buckling of the structure. During its growth period, the rigidity of the structure was tested by turning the prototype horizontally. While the hemp sagged under gravity and the load from one of the plates, the fibrous connections increased in structural strength as mycelium continuously grew, allowing the structure to withstand vertical forces.[252]

Material Understanding & Visual Acceptance: Chaos

The experiments resulted in a chaotic and unpredictable architecture, shifting away from discreet elements, but characterized by vagueness and singularities where system.[253] In this sense, decoration becomes structural, and the structure becomes ornamental, as *Living Fiber* displays a brutal yet fascinating aesthetic, especially in the transition between the chaotic and more rigorous parts (see figure 3.4.17).[254] The exploration of its visual characteristics centers on the self-organization and swarm intelligence of living mycelium. Moving beyond the repetitive and restricted formation of traditional mycelium-based composites, the bottom-up approach of the project highlights the unique properties of variation and differentiation, leading to a tectonic and aesthetic organization that emerges from natural systems. The project advocates for a radical interdisciplinary approach. The concepts laid out in the project ought to rethink technology in terms of ecologies rather than optimizing each component individually. By aiming to embed technology deeply into architectural surfaces, this interaction not only enhances functionality but inspires new ways of thinking utilizing materials and tools in architecture.



CHAOS

The project was a good example of showcasing and advocating for the chaotic nature and behaviour of biological materials. The Living Fibre prototype displays a brutal yet aesthetically pleasing structure that embraces the natural processes of mycelium in its living state.

Additionally, the project demonstrates the importance of external components as key factors in influencing the growth of mycelium.

3.5 The Senso-Aesthetics of Mycelium's Natural Processes: *Mycelium Rope*

Introduction: Senso-Aesthetics

In recent years, mycelium has increasingly been a subject of artistic research in the fields of Bio-Art, Science Art, and Post Media art, under the category of Hybrid Arts (see figure 3.5.1). The organism has become a crucial component in various artistic experiments and ongoing art interventions.[255] An example of this is the audio-visual installation *Myconnect* by Mirjan Svagelj and Anil Podgornik shown in figure 3.5.2, offering an experiential perspective on the connection between humans and fungi. The space offers an experiential perspective in which individuals engage in a biofeedback audio loop that illustrates the concept of companion-species.[256]

Despite this growing interest in the arts, within architecture its uptake has been slower. A survey conducted by Bonenberg et al. showed that only 56 percent of architects are aware of mycelium-based composites as a decorative material and even fewer recognize their usage as a structural or semi-structural material.[257] The finding suggests a gap in the appreciation of mycelium's capabilities to not only offer functional benefits but also enhance the visual aesthetics of architectural design. However, this study might also suggest that mycelium isn't offering any practical purposes to be applied in architectural works. An assumption by a few researchers and designers arose that the inherent variability in the visual characteristics of the composites presents a challenge for their adoption in architecture, as the materials exhibit non-uniform textures that change over time.[258] It is also important to consider that while human sensory experience uses all senses, visual perception often overshadows and takes precedence among the others.[259]

Bonenberg et al. explored public perceptions of decorative mycelium-based products through a survey of individuals in the architecture field. While the participants found the composites fascinating and sustainable, their fungal origin and unusual appearance raised some concerns (see figure 3.5.3).[260] The result of the study involving professional architects and interior designers indicated that while they are willing to utilize the properties of mycelium in architectural works, they are less inclined to use them for their own projects and have concerns about the material's nature.[261]

255. Anna Lewandowska, Agata Bonenberg, and Maciej Sydor, "Mycelium-Based Composites: Surveying Their Acceptance by Professional Architects," Biomimetics 9, no. 6 (June 2024): 1, https://doi.org/10.3390/biomimetics9060333.

256. Regine Rapp, "On Mycohuman Performances: Fungi in Current Artistic Research," Fungal Biology and Biotechnology 6, no. 1 (December 4, 2019): 2, https://doi.org/10.1186/s40694-019-0085-6.

257. Lewandowska, Bonenberg, and Sydor, "Mycelium-Based Composites." 10

258. Ibid. 2

259. Agata Bonenberg et al., "Mycelium Material in Interior Design. Acceptance Level amongst Future Users of New Eco-Aesthetics," March 10, 2023, https://doi.org/10.21203/rs.3.rs-2657767/v1. 2

260. Lewandowska, Bonenberg, and Sydor, "Mycelium-Based Composites." 2

261. Ibid. 3



Fig. 3.5.1 The use of mycelium in arts. *Lingzhi Girl* by Xiaojing Yan.



Fig. 3.5.2 The spatial installation *Myconnect* by Mirjan Svagelj and Anil Podgornik

In addition, due to the public's visual perception of fungi as inherently harmful organisms, concerns regarding the health effects of fungi pose another challenge in the upscaling of the composites despite being proven safer than conventional materials such as particleboards or fibreboards.[262] Researchers in interdisciplinary fields such as art and microbiology have expanded the understanding of what art means, leading to the development of new forms and methodologies in practices that engage with other living organisms. The art has shifted from being purely representational to becoming performative, interactive, and multidisciplinary. Living organisms act as mediums for experimental art that actively seeks to bridge the human with other scientific life forms.[263] An example of a project that exemplifies artistic experimentation that addresses the challenges of visual acceptance of mycelium-based composites within the architecture industry and bridges the gap between humans and biological organisms is *Mycelium Rope*.

262. Ibid. 2

263. Rapp, "On Mycohuman Performances." 7



Fig. 3.5.3. Natural appearance of mycelium on a tree trunk.

Overview: Mycelium Rope

Mycelium Rope, led by a London-based experimental architect and designer, Katya Bryskina, investigates interspecies collaboration to rethink the generation of soft megastructures through symbiotic collaboration between humans and microorganisms. As shown in figure 3.5.4, Bryskina's design lets mycelium evolve freely within a controlled incubator environment and is the artistic artifact itself. The work focuses on generating a suitable growth environment for bio-organisms to thrive, in this case, emphasizing the dynamic interactions between mycelium and a knitted formwork. In comparison to previously explored project, *BioKnit*, where inoculated substrates are embedded into the hollow cores of knitted textiles, *Mycelium Rope* allows for a more unrestricted mycelium overgrowth and colonization. Bryskina sees the incubator and the evolving mycelial structure within it not just as passive displays but as active participants in the creation of art that allows the audience to observe the evolution of the selected organisms.[264] The project not only challenges the traditional methods of mycelium composites grown in moulds but also invites the viewers to witness the unique biological aesthetics living mycelium has to offer. The series of curated experiments exhibited in Moskov displays the ambition to produce new types of complex morphologies, such as intricate three-dimensional structures and interwoven patterns, as well as weaving techniques to cultivate unique mycelial forms and growth performance.[265]

264. "Mycelium, Rope by Katya Bryskina – Future Materials Bank," accessed June 20, 2024, https://www.futurematerialsbank.com/material/mycelium-rope/.

265. "Mycelium, Rope by Katya Bryskina – Future Materials Bank."



Fig. 3.5.4 A zoomed in photograph of *Mycelium Rope.*

Design and Process

A key design aspect of the experiment *Mycelium Rope* that differentiates it from previous mycelial artistic explorations is its goal to merge the sophisticated, age-old practice of knitting methods with the unique biological processes of mycelium to preserve the creativity inherent in human craft while embracing the imperfect aesthetics of natural components (see figure 3.5.5). As automation challenges human biological nature, it becomes harder to accept nature's imperfections. The experiment intends to find the balance between the artificial and natural by combining traditional craftsmanship with bio-fabrication to retain a higher level of creativity found in human craft and acknowledge natural aesthetics.[266]



Fig. 3.5.5 Mycelium growing on the hand-knitted formwork of the project.

266. Elena Redaelli, "Interspecies Collaboration for Woven, Living Megastructures and Fibre-Based Composites in Katya Bryskina's Research," ARTEMORBIDA (blog), April 26, 2021, https://www.artemorbida.com/interspecies-collaboration-for-woven-living-megastructures-and-fibre-based-composites-in-katya-bryskinas-research/?lang=en.

267. Redaelli, "Interspecies Collaboration for Woven, Living Megastructures and Fibre-Based Composites in Katya Bryskina's Research."

268. Digital FUTURES Lecture: Living Megastructures. Nature-Inspired Design Strategy, 2021, https://www.youtube.com/watch?v=MZDRSwiiFj0.

As shown in figure 3.5.6, the design of the experimental project draws inspiration from soft systems constructing dynamic environments examples, such as spider nets, silkworms weaving, and mycelium networks.[267] Bryskina started the project by testing the structural performance of mycelium. While she found the structural performance to be lacking, the focus of the project shifted to the material's creative possibilities and its ability to form personal, expressive designs. The project exposes the knitted fabric backbone in the incubator to allow viewers to observe the stages of mycelium growth as it overtakes and conceals its knitted support, offering a deeper appreciation of the organic process and material's unique properties (see figure 3.5.7).[268]

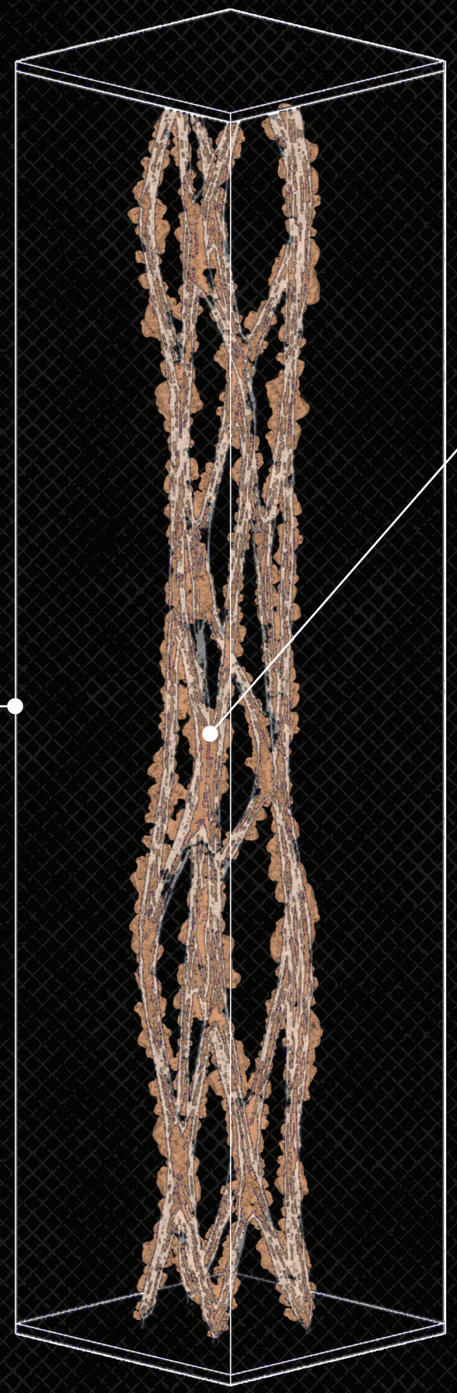


Fig. 3.5.6 (right) The view of the public looking into the incubator as mycelium grows.

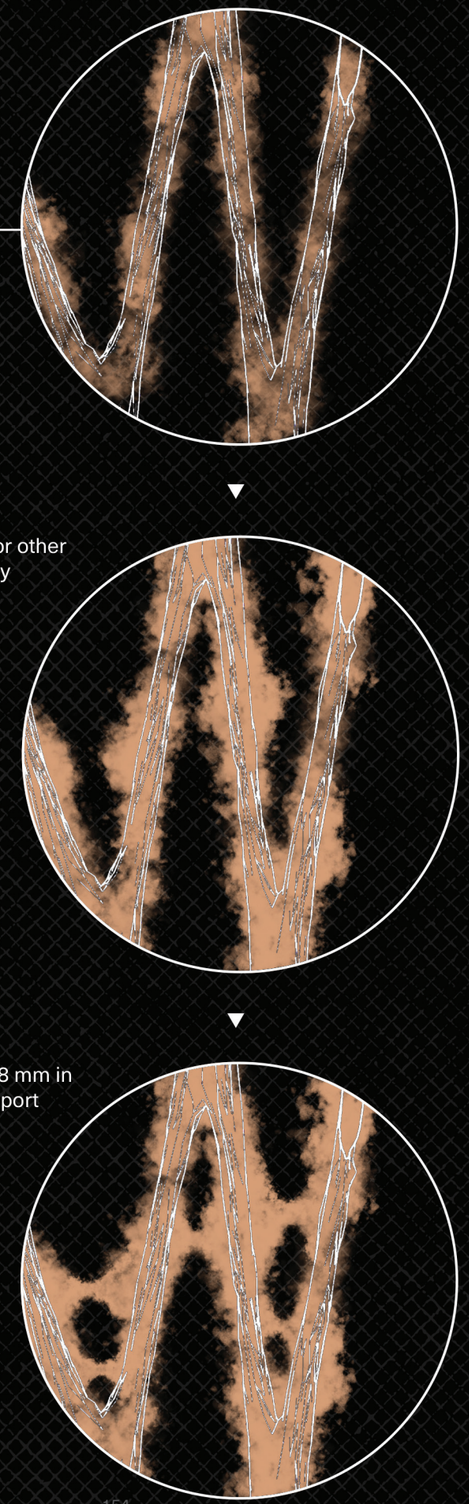
Fig. 3.5.7 (next page) A diagram of mycelium colonization bridging the gaps between spaces.

BRIDGING

One of the most interesting finding from the project is the ability of mycelium to bridge gaps of up to 8mm as seen in the illustration.



The column prototype also demonstrated how mycelium takes advantage of its base formwork as nutrient pathways, showing higher density in places where water and nutrients are present, slowly lowering as it moves up and receives less resources.



In addition, the experiment aims to trace the natural patterns of mycelium, to fully understand the organism and its functions with the goal of translating them into real life applications. She believes that understanding the properties of mycelium to partake in the whole process of a project, rather than its fragments, opens the possibilities of varying design strategies.[269] In *Mycelium Rope*, mycelium acts as a bonding agent that penetrates through the fibers of the knitted fabric and closes the gaps within the knitted fabric structure (see figure 3.5.8). By manipulating parameters such as light, air, and nutrients, unique structures can be cultivated. Moreover, there is freedom in choosing the collaborators as different types of fungi species, nutritional substrates, and methods of interactions as seen from other bio-fabricated projects.[270]

As shown in figure 3.5.9, the project consists of two different stages, The Dark and the Final Phase. The Dark Phase publicly exhibits the active process of mycelium growth and formation, where visitors are given the agency to influence the growth process by light manipulation, creating a sensory experience between the visitors and the project. In the Final Phase, the growth process is stopped by drying the mycelium-colonized framework that has been created, visualizing the deeper connection between nature and its viewers.[271]



Fig. 3.5.8 Mycelium overgrowth on its integral knitted formwork.

269. Digital FUTURES Lecture.

270. Ibid.

271. "IM-A Studio / LIFORM: Living Megastructures," Katya Bryskina, accessed June 8, 2024, https://www.katyabryskina.com/liform.

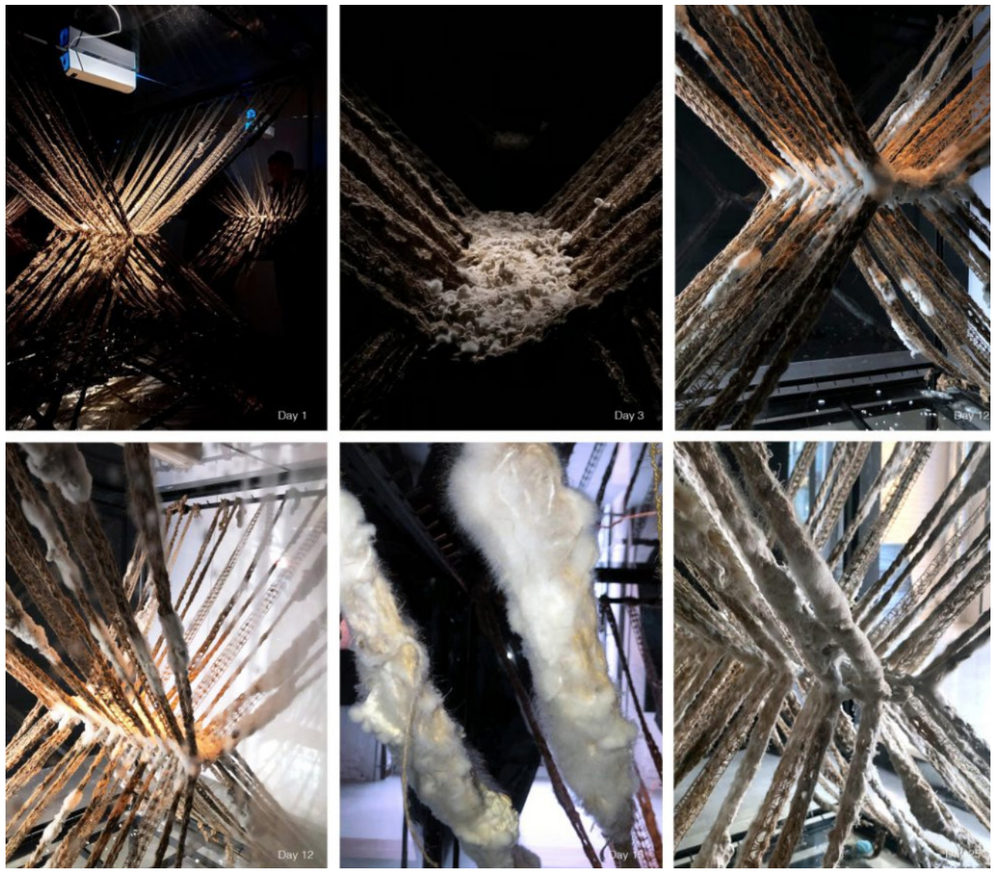


Fig. 3.5.9 Varying results of mycelium density in different areas of the formwork.

Fungal Species. The initial step in the project involves the selection and sourcing of the fungal species as the leading component of this collaborative experiment.[272] Two fungal species were considered for the LIFORM series: *Ganoderma Lingzhi* and *Pleurotus Ostreatus*. The latter was then chosen for the remainder of the project due to its rapid colonization rate and local availability, better meeting the needs of the experiment.[273]

Formwork Components. The design of the knitted formwork was primarily based on computational and mathematical principles, merged with the traditional handcrafting techniques. A crucial factor influencing the gap between ropes was the calculation of how far mycelium fibres can stretch without a supporting base or structure.[274] Although the weaved structure suggests directed and controlled mycelial growth, the knitting technique can be shaped into various forms, patterns, and combinations, which demonstrates the versatility of the traditional craft approach. As shown in figure 3.5.10, Bryskina designed three iterations of the project's knitted formwork base. The column-shaped formwork was specifically designed to observe how high mycelium can transfer water upwards, revealing that it could only reach thirty centimetres before colonization stops due to excess moisture. A second design aimed to observe how far mycelium could bridge freely in the air without a supporting formwork or structure. Lastly, the third iteration combined the two findings, designed approximately twenty-five centimeters in height, with specific rope distances to ensure proper colonization. Once the formworks were fabricated, liquid spawns cultivated in rye grains were dispersed on the surface to start the process of mycelium colonization.[275]



Fig. 3.5.10 Three different iterations of Katya Bryskina's *Mycelium Rope* for the LIFORM: Living Megastructures exhibit.

272. Digital FUTURES Lecture.

273. Bryskina, Katya (research and design lead). "Interview with Nixon Garcia". July 5, 2024.

274. Ibid.

275. Ibid.

276. Redaelli, "Interspecies Collaboration for Woven, Living Megastructures and Fibre-Based Composites in Katya Bryskina's Research."

277. Ibid.

Hardware and Software. Automation plays a significant role in the research, particularly in the integration of analog and computational processes. The balance between human craft and machines underscores the project's exploration of how recent technological advancements can augment natural processes. The automative weaving addresses the challenges of scalability and consistency often faced in bio-fabrication. However, it also acknowledges the intrinsic value of human imperfections, striving to harmonize artificial and natural aesthetics.[276]

Another vital component of the project is its use of bio-fabrication incubators designed to provide controlled environments to support mycelium growth. The incubators shown in figure 3.5.11 bring together the crafting techniques, technology, and living organisms that enable novel symbiotic interactions. By having the incubators clear and transparent, it allows the processes of mycelium to grow in air, forming in entirely new ways to be visible to its audience.[277]

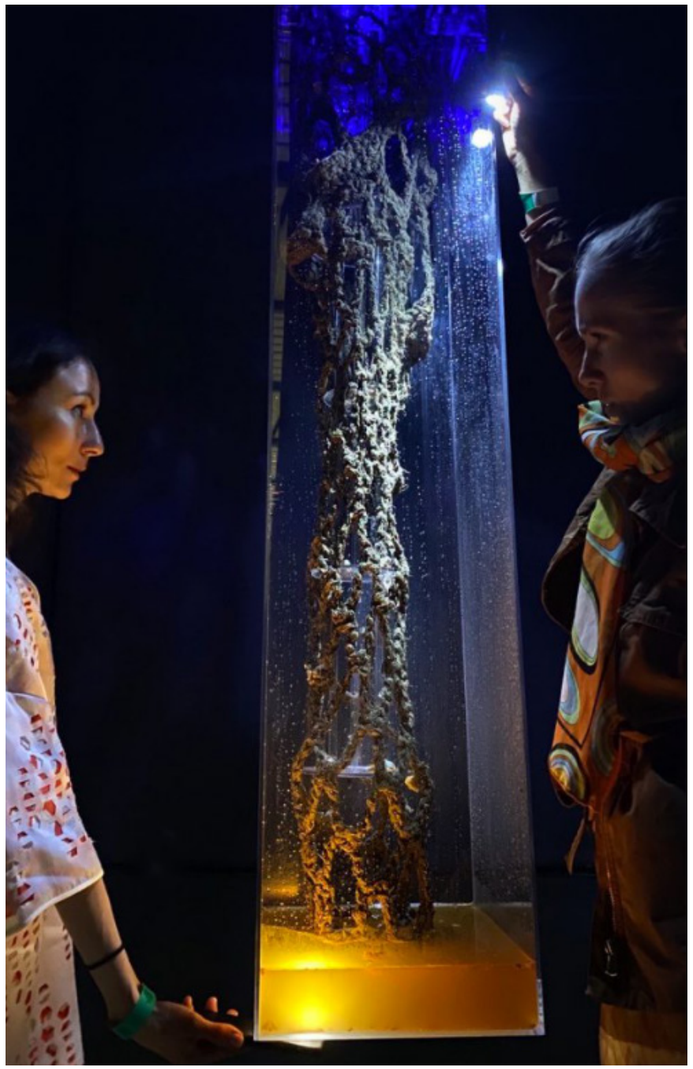


Fig. 3.5.11 A photograph of the incubator displaying an exposed mycelium growth process.

278. “Mycelium, Rope by Katya Bryskina – Future Materials Bank.”

279. Redaelli, “Interspecies Collaboration for Woven, Living Megastructures and Fibre-Based Composites in Katya Bryskina’s Research.”

280. Digital FUTURES Lecture.

281. “Mycelium, Rope by Katya Bryskina – Future Materials Bank.”

Growth Process. The main assembly technique executed in the project is the natural hyphal bonding of mycelium that allowed the organism to enswathe the weaved fibre structure gradually (see figure 3.5.12).[278] The growth process of mycelium, that ran for a duration of almost 4 weeks, is manipulated through the controlled environmental factors, significantly influencing the growth speed, direction, and structural characteristics of mycelium. The interspecies collaboration is constantly monitored and adjusted to achieve a more desirable and directed outcome.[279]

A series of photographs from the living growth process of the project demonstrate multiple strategies of how mycelium overtakes its base elements. The project observed rapid colonization of mycelium networks into the knitted structure, while the parts where nutrient collection occurred formed fluff-like balls to efficiently collect nutrients and thickened the base structural network, showing a resilient and adaptive natural process (see figure 3.5.13).[280] As the experiment went on, Bryskina constantly evaluated the entire process from its initial, growing, and drying phases, substrate composition, and structural outcomes (see figure 3.5.14). This approach allows her and the team to continuously reflect and discuss possible refinements of techniques and the exploration of new potentials in bio-fabrication.[281]

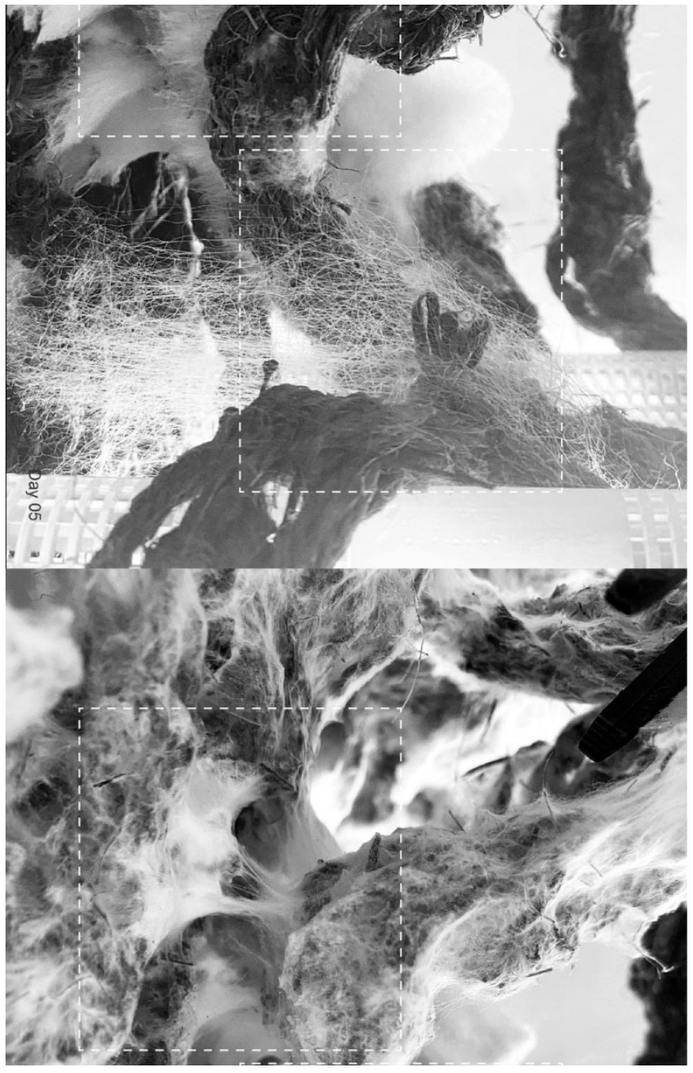


Fig. 3.5.12 Microscopic images of mycelium's colonization on the knitted textiles.

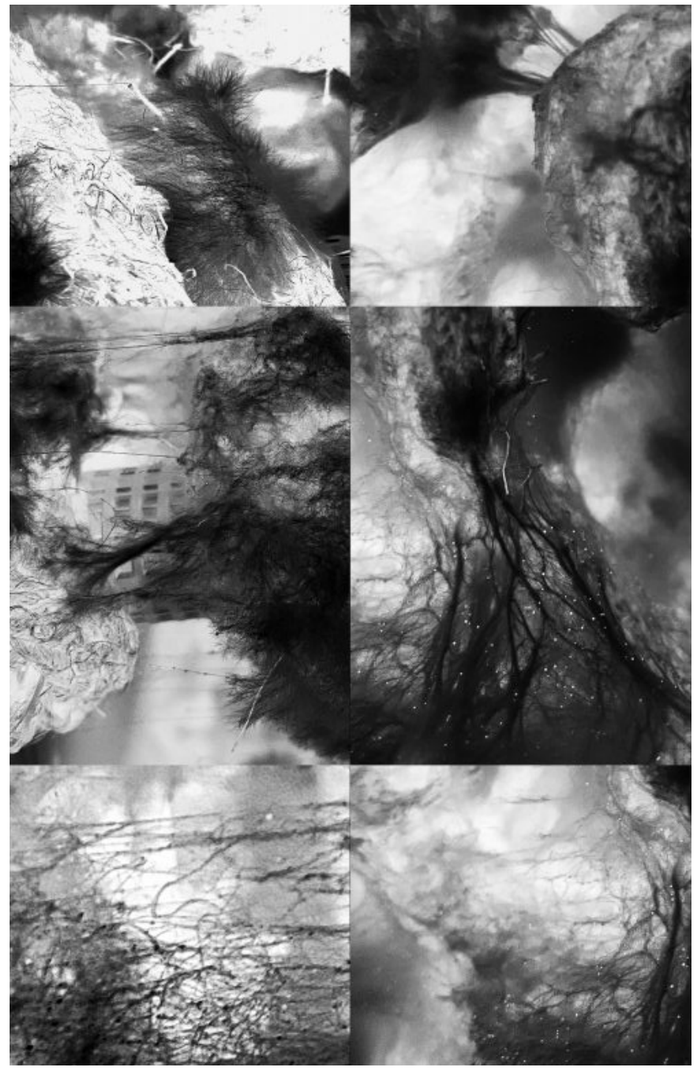


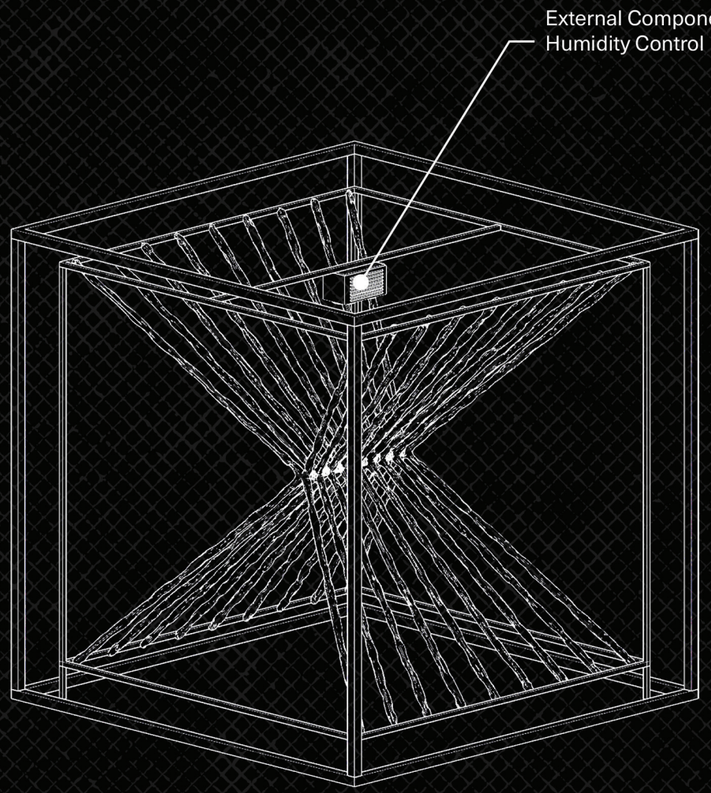
Fig. 3.5.13 Microscopic images of mycelium's capabilities to bridge gaps of up to 8 mm apart.

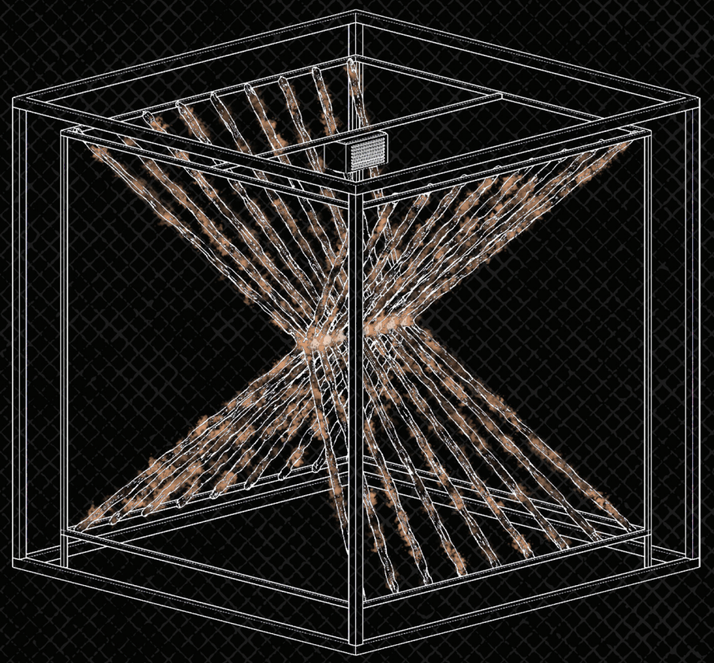
Fig. 3.5.14 A diagram of *Mycelium Rope's* growth process.

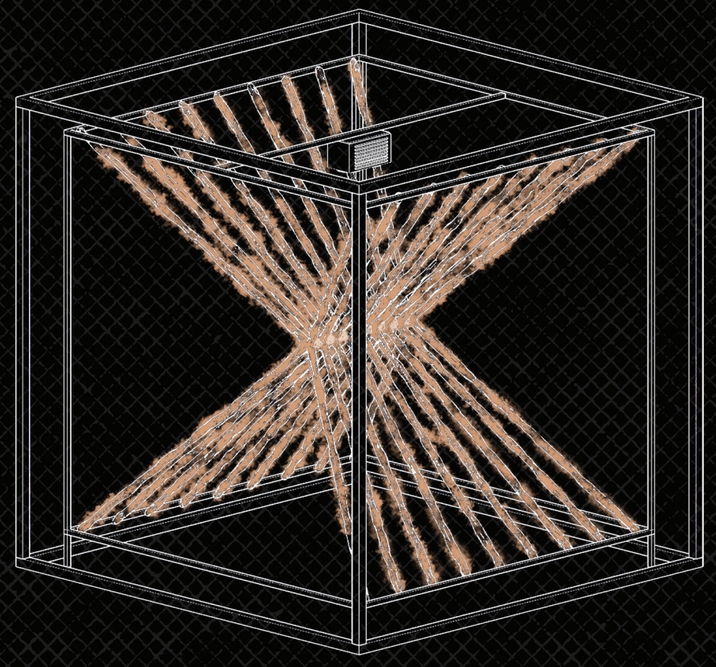
WEAVED GUIDANCE

Similar in some ways with BioKnit, but rather than filling the hollow cores of knitted textiles, Mycelium Rope employed surface inoculated with liquid spawn that allow mycelium to overgrow and conceal its initial textile base.

The project allows mycelium to grow in an influenced manner and introduce unique findings such as nutrient transfer and “air-growth”.







Reflection: Senso-Aesthetics as part of "The Living"

For Bryskina, the future is designing new ecosystems and potentially being the start of an innovative environment.[282] She suggested that designers must constantly reevaluate their relationship with nature and its processes to develop bio-fabrication practices in the industry. By doing so, Bryskina was able to evaluate and reflect on the challenges and knowledge gaps that previous mycelial projects encountered and address them for her project, *Mycelium Rope*.[283]

Biological Utilization: Influenced Growth

The experiment displayed the diverse strategies of mycelium interactions, such as rapid colonization of formwork, resilient morphological adaptation, and even unexpected fruiting under nutrient stress. For Bryskina, this natural progression from simple networks to complex interactions truly captured the essence of biomimicry and its potential for sustainable, nature-inspired architecture.[284] Typically working with a predefined or imposed form to appear similar to conventional building materials, *Mycelium Rope* shifts away from the form-making principles of traditional mycelium-based composites but rather, utilizes the natural processes of living mycelium to determine its own structural and aesthetic forms. The incubators present a whole new discussion on incorporating external components to mycelium-based projects aside from being used strictly for moulding purposes. These influential components in and out of the incubator played vital roles that involved guiding the organism's development using specific nutrients and conditions to create intricate and unique mycelial forms.

Integral & Lost Formwork: Weaving Guidance

The complex network of mycelium within a controlled environment acts as a bonding agent that penetrates the fibers and closes the gaps with new and complex patterns. As mentioned in *Mycera*, this is not a relatively new process and has been the primary method of bonding organic substrates to fabricate and produce most mycelium-based composites. However, the process was exploited even further in *Mycelium Rope*, which moved past binding closely packed substrates in moulds but rather bridged the gaps to form new surfaces and connect networks of up to 8 mm, transforming a two-dimensional image into a three-dimensional geometry. As living mycelium produces these new formations inside the incubator, the project also visualizes the intelligent characteristics of mycelium's resilient network that adapts based on their nutrient requirements and specific role within the connections.

282. "Katya, Artist and Architect — ArtyGeneration," accessed June 8, 2024, https://www.artygeneration.com/home/2020/4/12/katia-artist-and-architect.

283. Digital FUTURES Lecture.

284. Ibid.

285. Ibid.

Material Understanding & Visual Acceptance: Symbiotic Visualization

The series of installations by Bryskina not only showcase the unique characteristics of mycelium but also advocate for the use of the organism in bio-fabrication in its living state. The initiative highlights the distinct capabilities of mycelium, emphasizing its growth processes and binding functions. *Mycelium Rope* resonated deeply with the viewers, who appreciated observing the organic growth of the organism and its ability to create intricate fungal networks without human intervention (see figure 3.5.15). Most were intrigued by the visualization of a natural process that usually occurs underground in a different morphology that showcased its unique biological functions.[285] The art in this context involves the incorporation of mycelium in creating a harmonious ecosystem in an incubator. The incubators act as viewing screens for humans to witness the complex yet fascinating beauty of natural aesthetics, specifically the colonization of the living mycelium.

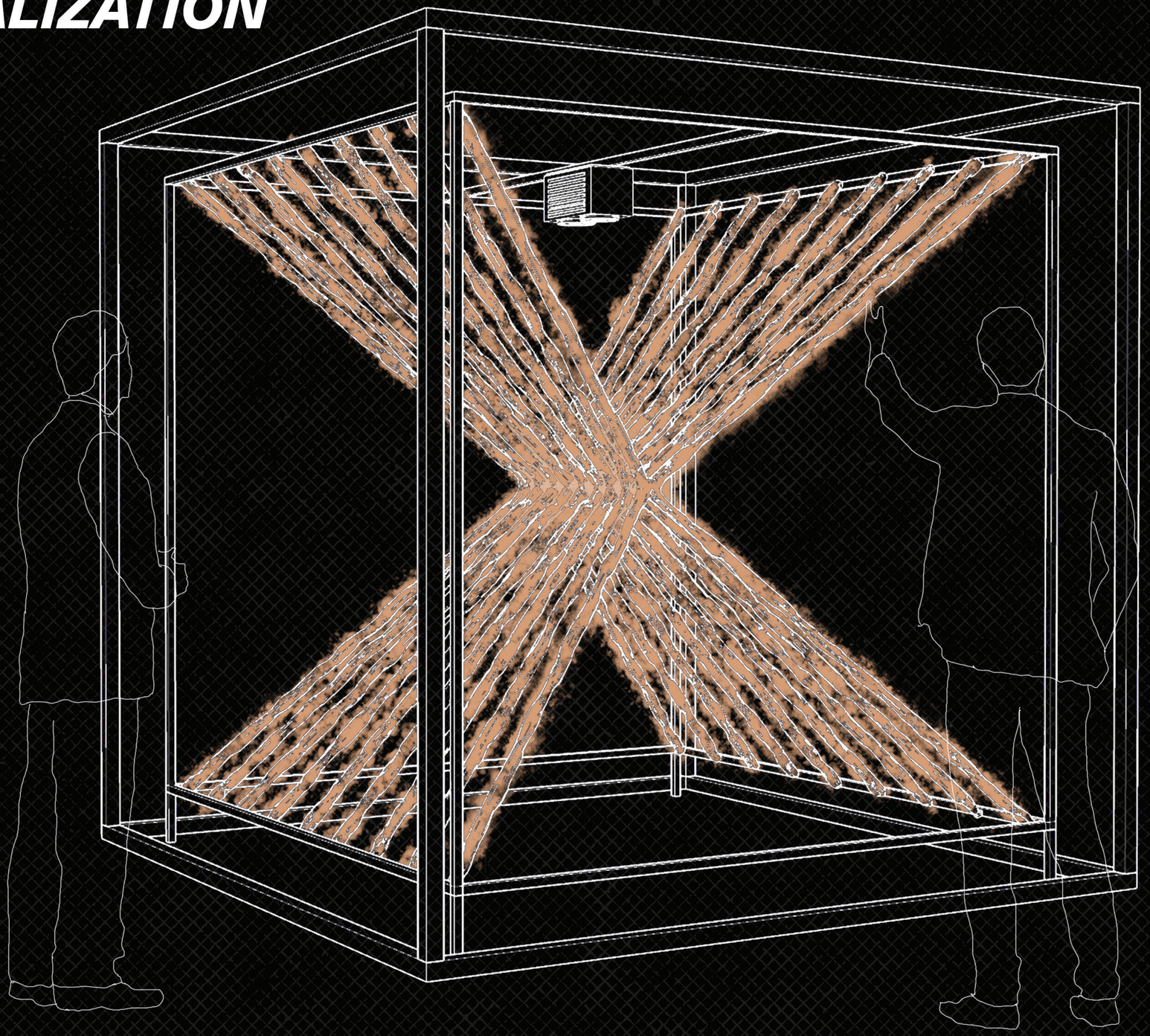
It is recognizable that the project and similar works in the living category are not primarily focused on creating fully operational or structurally sound structures. Instead, they aim to publicly demonstrate and present the natural biological processes of living mycelium. One of the project's key objectives is to inspire viewers by displaying harmonious environments where human and natural processes can collaborate. Furthermore, Bryskina is constantly seeking different types of collaborators for her projects in hopes of revealing unique methods of interaction. She believes that to push the boundaries of bio-fabrication, there should be constant changes in the collaborators and conditions of growth. Similar to *Mycelium Tectonics*, Bryskina's installations and a few projects within the living category are noticeably integrating more modern technological advancements to enhance the biological features offered by living mycelium. Specifically, the project aims to form spaces that balance analog and computation, natural and artificial, where nature and its processes can be part of a collaborative system that lets its intelligence fully unfold. Lastly, the project promotes a special relationship between humans and natural systems to engage in an interspecies learning process, constantly pushing boundaries and adjusting to each other.

Fig. 3.5.15 An illustration of the project's learning experience that fosters a deeper relationship between mycelium and its viewers.

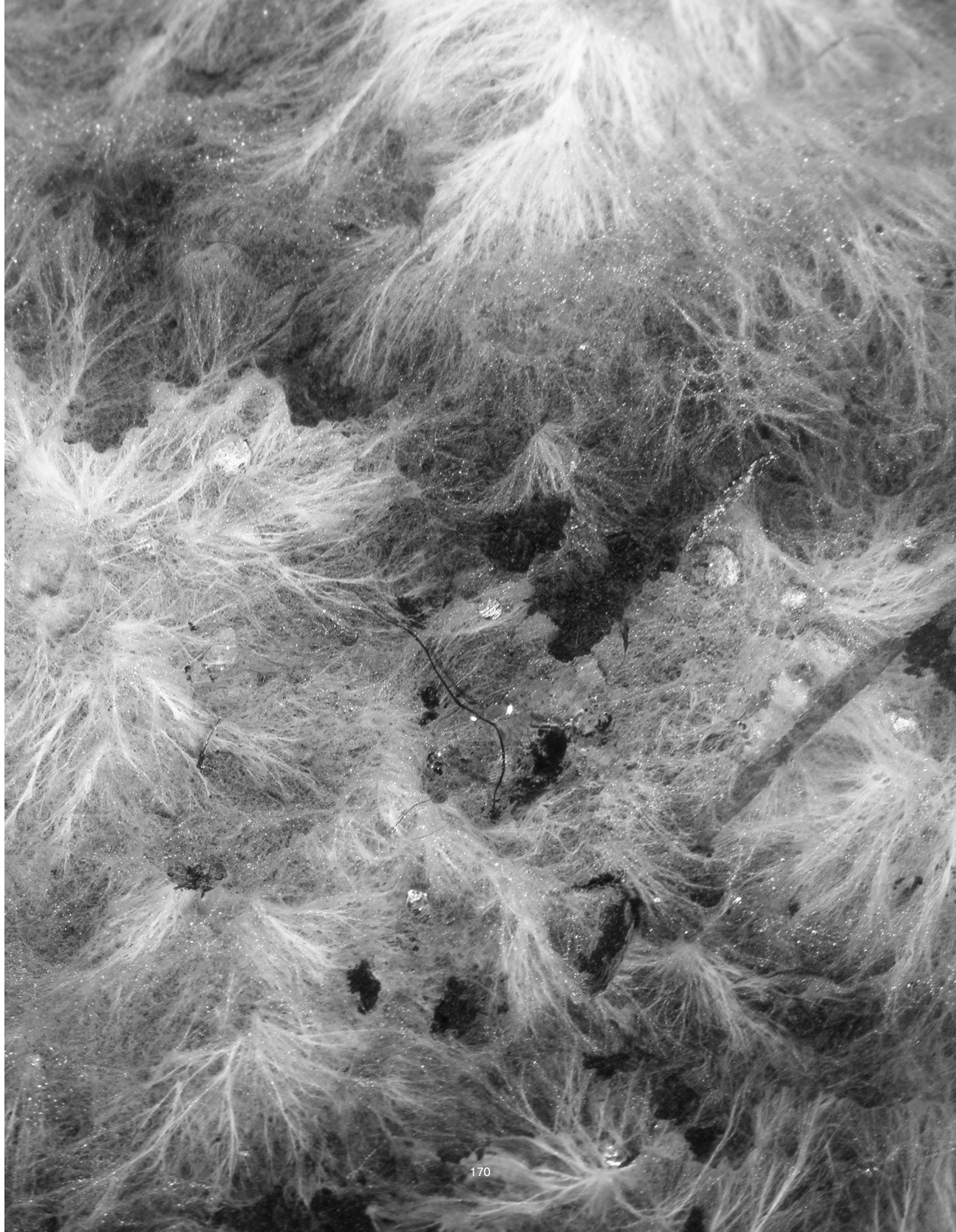
SYMBIOTIC VISUALIZATION

Katya Bryskina's concept of mycelium being the art itself allows the incubators to resonate deeply with its viewers, allowing an exposed, up-close observation of mycelium's growth.

The addition of external factors that were accessible for the public to tweak, such as lighting control, humidity level, and even sound, resulted in a deeper relationship between the humans and the art.



Chapter 4: Outlook



4.1 Conclusion

The Living Mycelium

The thesis aims to reveal the transformative potential of preserving mycelium in its living state to translate their innovative methodologies to mainstream architecture applications. Building upon the principles laid out by the “grow-kill” or as referred to as “nonliving” in the paper, the research highlights the unique biological processes of “living” mycelium architecture that includes self-repair, self-growth, self-organization, and environmental responsiveness. The thesis delves into the multifaceted applications of mycelium that involve the explored unique strategies and their respective projects. By analyzing these unique strategies, the research shared commonalities that emphasized three main topics: biological utilization, integral and lost formwork, and material understanding and visual acceptance.

Biological Utilization

Biological utilization examines how the natural biological properties of mycelium are harnessed, specifically illustrating the organism’s unique capabilities such as self-growth, self-repair, and self-organization. The following case studies exemplify the diverse applications of mycelium in architectural construction. *La Parete Fungina* and *Mycera* both focus on the myco-welding process, where mycelium’s hyphal bonding is utilized to bind substrates and units into cohesive structures. *BioKnit* introduces a different approach by showcasing the compatibility of mycelium with other biomaterials such as bacterial cellulose. *Mycelium Tectonics* explores the concept of bio-tectonics, fabricating prototypes that display the responsive characteristics of mycelium to its environment. Lastly, *Mycelium Rope* investigates the influenced growth of living mycelium, demonstrating how external factors play a role in the organism’s growth.

Myco-welding: As demonstrated in the project *La Parete Fungina*, myco-welding, or the binding capability of mycelium’s hyphal networks to combine modular units into one single structure. The hyphal bonding technique harnessed the organism’s ability to self-growth and self-repair, presenting a sustainable alternative to traditional mortar. The process addresses challenges faced in transportation and contamination control during construction as it allows the assembly of standard modular units in situ. Furthermore, the strategy offers a practical solution in reducing demands for labour and uncertainties during on-site assembly

Penetrate: Comparable to *La Parete Fungina, Mycera* also showcased the significant advantages of the myco-welding process. However, the project pushes the technique further and demonstrates a multiplanar assembly system that myco-welded the bars and nodes components, penetrating and seeping through the gaps of 3D-printed elements. The connections from the outside wall and hollow core areas show the complexity of mycelium’s colonizing characteristics

Myco-textile Colonization: Although sharing a similar approach to *Mycera* and *La Parete Fungina*, *BioKnit* emphasizes the potential of utilizing the living processes of mycelium alongside other biomaterials such as bacterial cellulose. By tinkering with mycelium and BC, the project unveiled special symbiotic relationships that could only be achieved by incorporating living organisms. Additionally, the project demonstrates the potential of textile knitted scaffolding to assemble multiple living composites facilitated by the self-growth process of living mycelium, colonizing the knitted base and transforming it into a coherent whole

Bio-tectonic: The project *Mycelium Tectonics* emphasizes the concept of tectonics, in which materials are used in ways that respect their innate. The project offered a model that explores the dynamic and adaptive behaviours of living mycelium systems. By harnessing the true biological characteristics of living mycelium, the project was able to construct a prototype that responds to its environment, suggesting a shift from traditional practice to construction approaches that incorporate living systems

Influenced Growth: Shifting away from the assumption that external components are primarily used for moulding purposes only, the incubators displayed in *Mycelium Rope* present a whole new discussion on incorporating external factors. The project harnesses the innate capabilities of mycelium to facilitate self-growth while introducing slightly engineered elements in growing chambers that influence the growth of the living organism. The chambers demonstrate the potential of influential factors that could be vital in guiding living systems to create intricate and unique mycelial forms.

Integral & Lost Formwork

The integral and lost formwork look into the methods of how base frameworks become one with mycelium as integral structural elements for these case studies. *La Parete Fungina* leverages hyphal bonding and lightweight mycelium-based blocks to create self-supporting units without external binding agents and reduced base formwork to minimize waste. *Mycera* takes a technology-aided design approach by combining mycelium with 3D-printed clay systems to explore mycelium’s reinforcing

properties. *BioKnit* employs a knitted textile system, acting both as a mould and integral support for a free-standing structure. *Mycelium Tectonics* introduces a composite formwork of hemp-fibre scaffolds, merging structural support with nutrient transfer networks. Lastly, *Mycelium Rope* challenges traditional formwork by demonstrating mycelium's capabilities of growing on unsupported areas, bridging gaps between the knitted formwork.
Standalone: Utilizing the myco-welding strategy along with the lightweight properties of mycelium-based composites, *La Parete Fungina* was able to produce a self-supporting unit with no external binding agents and very minimal recyclable supports. The project also employs reusable formwork systems for moulding the composite chunks, facilitating the production of large fungal blocks while minimizing waste often considered an issue in the nonliving fabrication process.

Reinforcement: *Mycera* highlights a bio-hybrid collaboration with the inclusion of biomaterials, clay, and 3D-printed systems. Revealing an unrecognized capability for the mycelium to penetrate porous walls of clay structures, the method results in an increase in the structural integrity of the clay components due to the additional fibre reinforcement provided by mycelium. The findings discovered in the experiment bypass existing structural and fabrication restrictions in mycelium, clay, and 3D-printing processes.

Knitted Scaffold: A key aspect of the project, *BioKnit*, is its use of knitted textile formwork that serves as a soft formwork for the inoculated mycelium substrate, referred to as mycocrete in the project. This strategy of incorporating the formwork as integral structural support of the prototype addresses the waste issues of the nonliving projects without the need for external support.

Machinic: *Mycelium Tectonics* applies a unique composite formwork system that supports mycelial growth on modified three-dimensional hemp-fibre scaffolds. The project expands on the advancements of readily available tools, resulting in a fibrous formwork that provides structural support and acts as a nutrient source that facilitates the organism's growth and development.

Weaving Guidance: The structural framework of *Mycelium Rope* challenges the traditional concept of formwork by creating a knitted base that guides the overgrowth and colonization of mycelium without any restrictions. Following the same idea as presented in other projects,

the biological process of mycelium facilitates the bonding of the organic fibres that support it. However, the project further exploits the process that results in bridging gaps, transforming two-dimensional images into three-dimensional geometries.

Material Understanding & Visual Acceptance

Material understanding and visual acceptance emphasize the role of collaboration and the influence of mycelium's natural aesthetic on the public's acceptance of the material. The following projects collectively demonstrate how collaboration and a deeper understanding of mycelium can push the boundaries of mycelial architecture. *La Parete Fungina* demonstrates an interactive collaborative experience that fosters an exchange of knowledge that plays a role in advancing research on mycelium. *Mycera* highlights the need for interdisciplinary collaboration, particularly between bio-fabrication and 3D printing to create adaptable material systems. *BioKnit* explores and embraces the natural imperfections of mycelium and bacterial cellulose as a key element of its design. *Mycelium Tectonics* also embraces the chaotic and unpredictable nature of living mycelium as seen in its prototypes. Lastly, *Mycelium Rope* serves as a visualization of the intersection between architecture, art, and science, exposing the natural growth process of mycelium to the public eye.

Interactive & Collaborative: The students and faculty involved in the design exhibition of the prototype *La Parete Fungina* showed appreciation for the collaborative experience offered by the project. The highly engaging workshop achieved an exchange of resources and information that was beneficial in developing the research of living mycelium.

Myco-extrusion: *Mycera* emphasizes the need for interdisciplinary collaboration, in this case between mycology, bio-based fabrication, and 3D printed advancements, to develop unique and innovative material systems. Furthermore, the project advances the exploration within these collaborative systems with the incorporation of living organisms to enhance structures' adaptability and resilience.

Imperfections: *BioKnit*, presents the potential of collaboration in architecture and design to produce not only durable structures but also aesthetically pleasing visuals of natural components. The project serves as an inspiration to embrace the natural impurities of biomaterials, as it is evident that no concealment and touch-ups

were applied to the final prototype, exhibiting the organic and natural aesthetics of each organism's patterns and textures.

Chaos: Though it may appear chaotic, the prototypes produced in *Mycelium Tectonics* exhibit a brutal yet fascinating aesthetic. The models display an unpredictable architecture that drifts away from the discreet element assembly but is rather defined by the features that emerge from its evolving system. Furthermore, the project lays out a concept to rethink technology in terms of ecologies and utilize digital simulation techniques to open new possibilities for integrating living systems into mainstream construction applications.

Symbiotic Visualization: *Mycelium Rope* is a testament to the potential of a unique intersection between art, science, and architecture. Serving as both a canvas and the art itself, the incubators expose the complex beauty of mycelium's natural aesthetics and processes while challenging the notions of traditional building materials and methods. Moreover, the project serves as an inspiration that displays a harmonious environment where humans and natural processes can collaborate by preserving the beauty of human craft combined with advanced digital fabrication techniques.

4.2 Reflection

Outlook

The paper highlights the most frequently utilized biological advantage of living mycelium which is its hyphal-bonding process, referred to as "myco-welding" in this paper. When used as a binding material for loose substrates or components, mycelium exhibits properties that could potentially replace traditional mortar. In projects like *La Parete Fungina* and *Mycera*, the organism's self-growth capabilities allow the penetration of small gaps and interconnect with other mycelial networks in proximity, effectively bonding elements together. This process allows for a more labour-efficient approach that requires fewer resources as compared to traditional mortar. Moreover, as showcased by *Modular Mycelia*, mycelium adapts well to multi-scalar assembly systems, binding units of varying sizes to create intricate forms and geometries. This finding offers insights into the potential of living mycelium as a bonding agent for adaptive and responsive modular screening facade systems. Additionally, the unique findings in *Mycelium Rope* indicate that mycelium can bridge gaps between knitted units, which could provide both insulation and aesthetic appeal in fungal screening systems. Although *Mycera* primarily employed mycelium for myco-welding, there is also potential in 3D printing with pre-inoculated mixtures, which would allow mycelium to grow within the microscopic gaps of the printed elements as they dry and cure.

Another advantage of using living mycelium in architecture and construction is its form-flexibility, as illustrated in projects such as *Mycelium Rope*, *Mycelium Tectonics*, and *BioKnit*. These projects demonstrate mycelium's ability to adapt to complex shapes, allowing the creation of intricate and even self-supporting structures. The form-adaptive properties of mycelium offer a sustainable alternative to traditional cast-in-place methods, allowing for the production of unique geometries without the high carbon emissions associated with concrete. This capability is particularly beneficial when incorporated with digital simulations of mycelial growth, aligning with the growing trend of parametric computer-aided design in contemporary construction practices.

However, the paper also puts emphasis on the limitations of using living mycelium in architecture, which may hinder its broader application in mainstream construction. Structurally, mycelium alone cannot replace conventional load-bearing materials like concrete or steel. Without adequate support or formwork, mycelium lacks the rigid structural support to provide compressive and tensile strengths

comparable to those of traditional structural materials. Additionally, mycelium can be brittle when dried, making it prone to cracking or breaking under stress. As an organic material, mycelium-based composites are prone to degradation over time, as evidenced by the *Monolito Micelio* prototype, which eventually collapsed. Nevertheless, as shown in *Mycera* and *BioKnit*, mycelium remains promising as a reinforcing element, potentially enhancing the structural integrity of materials such as clay and knitted textiles.

While mycelium, living or nonliving, remains a marginal and niche material seeking a wider adoption in mainstream applications, its potential in design and construction presented in this thesis remains strong. Like many other research fields, continuous exploration is essential to develop a stronger material understanding and to push the boundaries of what is possible. The more engagement with living organisms and systems, the greater the potential for innovative and sustainable design and building approaches to emerge.

Bibliography

Abdallah, Yomna K., and Alberto T. Estévez. “Biowelding 3D-Printed Biodigital Brick of Seashell-Based Biocomposite by Pleurotus Ostreatus Mycelium.” Biomimetics 8, no. 6 (October 2023): 504. https://doi.org/10.3390/biomimetics8060504.

Agraviador, Armand, Jane Scott, Romy Kaiser, Elise Elsacker, Aileen Hoenerloh, Ahmet Topcu, and Ben Bridgens. “Computation and Material Investigation in the Design of Biohybrid Textiles towards Architectural Integration,” n.d.

Almpani-Lekka, Dimitra, Sven Pfeiffer, Christian Schmidts, and Seung-il Seo. “A Review on Architecture with Fungal Biomaterials: The Desired and the Feasible.” Fungal Biology and Biotechnology 8, no. 1 (November 19, 2021): 17. https://doi.org/10.1186/s40694-021-00124-5.

Antonelli, Paola. The Neri Oxman Material Ecology Catalogue. New York: The Museum of Modern Art, 2020.

Arifin, Yusnani Hajar, and Yusri Yusuf. “Mycelium Fibers as New Resource for Environmental Sustainability.” Procedia Engineering, Malaysian Technical Universities Conference on Engineering & Technology 2012, MUCET 2012, 53 (January 1, 2013): 504–8. https://doi.org/10.1016/j.proeng.2013.02.065.

Attias, Noam, Ofer Danai, Ezri Tarazi, Idan Pereman, and Yasha J. Grobman. “Implementing Bio-Design Tools to Develop Mycelium-Based Products.” The Design Journal 22, no. sup1 (April 1, 2019): 1647–57. https://doi.org/10.1080/14606925.2019.1594997.

Bell, Fiona. “Upcycle Inspiration: Mycelium.” Aesthetics of Design (blog), January 27, 2020. https://www.aesdes.org/2020/01/27/upcycle-inspiration-mycelium/.

Bhardwaj, Abhinav, Al Mazedur Rahman, Xingjian Wei, Zhijian Pei, David Truong, Matt Lucht, and Na Zou. “3D Printing of Biomass–Fungi Composite Material: Effects of Mixture Composition on Print Quality.” Journal of Manufacturing and Materials Processing 5, no. 4 (2021): 112. https://doi.org/10.3390/jmmp5040112.

Biala, Eliza, and Martin Ostermann. “Mycostructures—Growth-Driven Fabrication Processes for Architectural Elements from Mycelium Composites.” Architecture, Structures and Construction 2, no. 4 (December 1, 2022): 509–19. https://doi.org/10.1007/s44150-022-00073-6.

“BioKnit Prototype – HBBE.” Accessed December 4, 2023. http://bbe.ac.uk/bioknit-prototype/.

Bitting, Selina, Tiziano Derme, Juney Lee, Tom Van Mele, Benjamin Dillenburger, and Philippe Block. “Challenges and Opportunities in Scaling up Architectural Applications of Mycelium-Based Materials with Digital Fabrication.” Biomimetics 7, no. 2 (April 14, 2022): 44. https://doi.org/10.3390/biomimetics7020044.

Bonenberg, Agata, Maciej Sydor, Grzegorz Cofta, Beata Doczekalska, and Klaudia Grygorowicz-Kosakowska. “Mycelium-Based Composite Materials: Study of Acceptance.” Materials 16, no. 6 (March 1, 2023): NA-NA. https://doi.org/10.3390/ma16062164.

Bonenberg, Agata, Maciej Sydor, Beata Doczekalska, Grzegorz Cofta, and Klaudia Grygorowicz-Kosakowska. “Mycelium Material in Interior Design. Acceptance Level amongst Future Users of New Eco-Aesthetics,” March 10, 2023. https://doi.org/10.21203/rs.3.rs-2657767/v1.

Boswell, Graeme P., Helen Jacobs, Karl Ritz, Geoffrey M. Gadd, and Fordyce A. Davidson. “The Development of Fungal Networks in Complex Environments.” Bulletin of Mathematical Biology 69, no. 2 (February 1, 2007): 605–34. https://doi.org/10.1007/s11538-005-9056-6.

Campbell, Sean, David Correa Zuluaga, Dylan Wood, and Achim Menges. “Modular Mycelia: Scaling Fungal Growth for Architectural Assembly,” 2017.

Cecchini, Cecilia. “Bioplastics Made from Upcycled Food Waste. Prospects for Their Use in the Field of Design.” The Design Journal 20 (July 28, 2017): S1596–1610. https://doi.org/10.1080/14606925.2017.1352684.

Chen, Huaiyou, Amanmyrat Abdullayev, Maged F. Bekheet, Bertram Schmidt, Isabel Regler, Carsten Pohl, Cekdar Vakifahmetoglu, et al. “Extrusion-Based Additive Manufacturing of Fungal-Based Composite Materials Using the Tinder Fungus Fomes Fomentarius.” Fungal Biology and Biotechnology 8, no. 1 (December 21, 2021): 21. https://doi.org/10.1186/s40694-021-00129-0.

Dahmen, Joseph. “Soft Futures: Mushrooms and Regenerative Design.” Journal of Architectural Education 71, no. 1 (January 2, 2017): 57–64. https://doi.org/10.1080/10464883.2017.1260927.
———. “Soft Matter: Responsive Architectural Operations.” Technoetic Arts: A Journal of Speculative Research 14, no. 1/2 (June 2016): 113–25. https://doi.org/10.1386/tear.14.1-2.113_1.

Darwish, Leila. Earth Repair: A Grassroots Guide to Healing Toxic and Damaged Landscapes. Gabriola Island, BC: New Society Publishers, 2013.

Davidson, F.A. “Mathematical Modelling of Mycelia: A Question of Scale.” Fungal Biology Reviews 21, no. 1 (2007): 30–41. https://doi.org/10.1016/j.fbr.2007.02.005.

Day 4. DigitalFutures LIFORM:Living Megastructures, 2021. https://www.youtube.com/watch?v=OkCeRKAtggI.

dbt. “The Living Column,” April 26, 2022. https://dbt.arch.ethz.ch/course/the-living-column/.

Design and Violence. “Mycotecture (Phil Ross),” February 12, 2014. http://designandviolence.moma.org/mycotecture-phil-ross/.

Dessi-Olive, Jonathan. “Strategies for Growing Large-Scale Mycelium Structures.” Biomimetics 7, no. 3 (September 2022): 129. https://doi.org/10.3390/biomimetics7030129.

Dezeen. “Beetles 3.3 and Yassin Arredia Design Use Fungus for Pavilion in Kerala,” August 26, 2017. https://www.dezeen.com/2017/08/26/shell-mycelium-fungus-pavilion-beetles-3-3-yassin-arredia-design-kerala-india/.

Dezeen. “Blast Studio 3D Prints Column from Mycelium to Make ‘Architecture That Could Feed People,’” January 18, 2022. https://www.dezeen.com/2022/01/18/blast-studio-tree-column-mycelium-design/.

Digital FUTURES Lecture: Living Megastructures. Nature-Inspired Design Strategy, 2021. https://www.youtube.com/watch?v=MZDRSwiiFj0.

“El Monolito Micelio — Jonathan Dessi-Olive.” Accessed August 13, 2024. https://jdovaults.com/El-Monolito-Micelio.

Elise Elsacker. “BioKNIT: Strategies for Living Textile Architectures.” Accessed December 4, 2023. https://www.eliseelsacker.com/research/bioknit-strategies-for-living-textile-architectures.

Elsacker, Elise, Eveline Peeters, and Lars De Laet. “Large-Scale Robotic Extrusion-Based Additive Manufacturing with Living Mycelium Materials.” Sustainable Futures 4 (2022): 100085. https://doi.org/10.1016/j.sftr.2022.100085.

Elsacker, Elise, Simon Vandelook, Bastien Damsin, Aurélie Van Wylick, Eveline Peeters, and Lars De Laet. “Mechanical Characteristics of Bacterial Cellulose-Reinforced Mycelium Composite Materials.” Fungal Biology and Biotechnology 8, no. 1 (December 4, 2021): 18. https://doi.org/10.1186/s40694-021-00125-4.

Elsacker, Elise, Simon Vandelook, Aurélie Van Wylick, Joske Ruytinx, Lars De Laet, and Eveline Peeters. “A Comprehensive Framework for the Production of Mycelium-Based Lignocellulosic Composites.” Science of The Total Environment 725 (July 2020): 138431. https://doi.org/10.1016/j.scitotenv.2020.138431.

G. Greca, Luiz, Janika Lehtonen, Blaise L. Tardy, Jiaqi Guo, and Orlando J. Rojas. “Biofabrication of Multifunctional Nanocellulosic 3D Structures: A Facile and Customizable Route.” Materials Horizons 5, no. 3 (2018): 408–15. https://doi.org/10.1039/C7MH01139C.

Glass, N. Louise, Carolyn Rasmussen, M. Gabriela Roca, and Nick D. Read. “Hyphal Homing, Fusion and Mycelial Interconnectedness.” Trends in Microbiology 12, no. 3 (March 1, 2004): 135–41. https://doi.org/10.1016/j.tim.2004.01.007.

Hawkins, Heidi-Jayne, Rachael I.M. Cargill, Michael E. Van Nuland, Stephen C. Hagen, Katie J. Field, Merlin Sheldrake, Nadejda A. Soudzilovskaia, and E. Toby Kiers. “Mycorrhizal Mycelium as a Global Carbon Pool.” Current Biology 33, no. 11 (June 2023): R560–73. https://doi.org/10.1016/j.cub.2023.02.027.

Heaton, Luke, Boguslaw Obara, Vincente Grau, Nick Jones, Toshiyuki Nakagaki, Lynne Boddy, and Mark D. Fricker. “Analysis of Fungal Networks.” Fungal Biology Reviews 26, no. 1 (2012): 12–29. https://doi.org/10.1016/j.fbr.2012.02.001.

Hoenerloh, Aileen, Dilan Ozkan, and Jane Scott. “Multi-Organism Composites: Combined Growth Potential of Mycelium and Bacterial Cellulose.” Biomimetics (Basel, Switzerland) 7, no. 2 (2022): 55-. https://doi.org/10.3390/biomimetics7020055.

“Hy-Fi.” Accessed September 19, 2023. https://www.holcimfoundation.org/projects/hy-fi.

Ibrahim, Fatima, Giorgio Castellano, Olga Beatrice Carcassi, and Ingrid Maria Paoletti. “MycoCode: Development of an Extrudable Paste for 3D Printing Mycelium-Bound Composites.” In Architecture and Design for Industry 4.0: Theory and Practice, edited by Maurizio Barberio, Micaela Colella, Angelo Figliola, and Alessandra Battisti, 503–19. Cham: Springer International Publishing, 2024. https://doi.org/10.1007/978-3-031-36922-3_29.

Jauk, Julian, Lukas Gosch, Hana Vašatko, Ingolf Christian, Anita Klaus, and Milena Stavric. “MyCera. Application of Mycelial Growth within Digitally Manufactured Clay Structures.” International Journal of Architectural Computing 20, no. 1 (March 1, 2022): 31–40. https://doi.org/10.1177/14780771221082248.

Jauk, Julian, Hana Vašatko, Lukas Gosch, and Milena Stavric. MYCERA A Sustainable Future Building Material Consisting of Clay and Mycelium, 2021.

Jones, Mitchell, Andreas Mautner, Stefano Luenco, Alexander Bismarck, and Sabu John. “Engineered Mycelium Composite Construction Materials from Fungal Biorefineries: A Critical Review.” Materials & Design 187 (February 1, 2020): 108397. https://doi.org/10.1016/j.matdes.2019.108397.

Kaiser, Romy, Ben Bridgens, Elise Elsacker, and Jane Scott. “BioKnit: Development of Mycelium Paste for Use with Permanent Textile Formwork.” Frontiers in Bioengineering and Biotechnology 11 (2023): 1229693–1229693. https://doi.org/10.3389/fbioe.2023.1229693.

Kaiser, Romy, Jane Scott, Martyn Dade-Robertson, and Elise Elsacker. “Knit-Mycelium Hybrids: Designing and Scaling up with Bio Fabrication Systems Based on Mycocrete Injection in 3D Knitted Tubular Formworks.” Textile Intersections Conference Series, September 20, 2023. https://dl.designresearchsociety.org/textileintersections/textileintersections2023/researchpapers/2.

Karana, Elvin, Davine Blauwhoff, Erik-Jan Hultink, and Serena Camere. “When the Material Grows: A Case Study on Designing (with) Mycelium-Based Materials” 12, no. 2 (2018).

“Katya, Artist and Architect — ArtyGeneration.” Accessed June 8, 2024. https://www.artygeneration.com/home/2020/4/12/katia-artist-and-architect.

Katya Bryskina. “IM-A Studio / LIFORM: Living Megastructures.” Accessed June 8, 2024. https://www.katyabryskina.com/liform.

LaGreca, Scott. “McCoy, Peter. (2016): Radical Mycology: A Treatise on Seeing and Working with Fungi.” Symbiosis 71, no. 2 (February 1, 2017): 165–66. https://doi.org/10.1007/s13199-016-0460-5.

Leschok, Matthias, and Benjamin Dillenburger. “3D Printed Formwork for Mycelium Bound Composites,” 2023.

Lewandowska, Anna, Agata Bonenberg, and Maciej Sydor. “Mycelium-Based Composites: Surveying Their Acceptance by Professional Architects.” Biomimetics 9, no. 6 (June 2024): 333. https://doi.org/10.3390/biomimetics9060333.

"LIFORM: Living Megastructures." Accessed June 8, 2024. https://www.digitalfutures.world/workshops/history/view?workshops=67&cid=32&year=2021.

Livne, Achiya, Han A. B. Wösten, David Pearlmutter, and Erez Gal. "Fungal Mycelium Bio-Composite Acts as a CO2-Sink Building Material with Low Embodied Energy." ACS Sustainable Chemistry & Engineering 10, no. 37 (September 19, 2022): 12099–106. https://doi.org/10.1021/acssuschemeng.2c01314.

Manan, Sehrish, Muhammad Wajid Ullah, Mazhar Ul-Islam, Omar Mohammad Atta, and Guang Yang. "Synthesis and Applications of Fungal Mycelium-Based Advanced Functional Materials." Journal of Bioresources and Bioproducts 6, no. 1 (February 1, 2021): 1–10. https://doi.org/10.1016/j.jobab.2021.01.001.

McGaw, Janet, Alex Andrianopoulos, and Alessandro Liuti. "Tangled Tales of Mycelium and Architecture: Learning From Failure." Frontiers in Built Environment 8 (2022). https://www.frontiersin.org/articles/10.3389/fbuil.2022.805292.

Mediamatic. "Fungal Futures." Accessed December 10, 2023. http://www.mediamatic.net/en/page/242311/fungal-futures.

Meskauskas, A., M.D. Fricker, and D. Moore. "Simulating Colonial Growth of Fungi with the Neighbour-Sensing Model of Hyphal Growth." Mycological Research 108, no. 11 (2004): 1241–56. https://doi.org/10.1017/S0953756204001261.

Modanloo, Behzad, Ali Ghazvinian, Mohammadreza Matini, and Elham Andaroodi. "Tilted Arch; Implementation of Additive Manufacturing and Bio-Welding of Mycelium-Based Composites." Biomimetics 6, no. 4 (December 2021): 68. https://doi.org/10.3390/biomimetics6040068.

Mohseni, Alale, Fabricio Rocha Vieira, John A. Pecchia, Benay G&uuml, and rsoy. "Three-Dimensional Printing of Living Mycelium-Based Composites: Material Compositions, Workflows, and Ways to Mitigate Contamination." Biomimetics 8, no. 2 (June 1, 2023): NA-NA. https://doi.org/10.3390/biomimetics8020257.

"Mycelium – Future Materials Bank." Accessed March 7, 2024. https://www.futurematerialsbank.com/material/mycelium-clay/.

"Mycelium Mockup | Sala.Ubc.Ca." Accessed September 11, 2023. https://sala.ubc.ca/work/mycelium-mockup.

"Mycelium, Rope by Katya Bryskina – Future Materials Bank." Accessed June 20, 2024. https://www.futurematerialsbank.com/material/mycelium-rope/.

mycelium tectonics. "mycelium tectonics," May 1, 2015. https://mycelium-tectonics.com/.

"Mycelium Tectonics – Materiability." Accessed June 11, 2024. https://materiability.com/portfolio/mycelium-tectonics/.

"MycoKnit - College of Arts & Architecture." Accessed March 18, 2024. https://arts.psu.edu/projects/mycoknit/.

"Nature's Mysterious Networks: Mushrooms, Mycelia and Yeasts - GroundWork," April 13, 2021. https://www.groundworkgallery.com/exhibition/natures-mysterious-networks-mushrooms-mycelia-and-yeasts/, https://www.groundworkgallery.com/exhibition/natures-mysterious-networks-mushrooms-mycelia-and-yeasts/.

"NEWS - Klarenbeek & Dros - Designers of the Unusual." Accessed August 13, 2024. https://www.ericklarenbeek.com/.
Ng, Wasabii, Bahar Barati, and Elvin Karana. "Healing with Fungi: Unique Aesthetic Expressions for Mycelium-Based Materials Through Patch and Mend," 3253–67, 2022. https://doi.org/10.1007/978-981-19-4472-7_210.

Nguyen, Mai Thi, Daniela Solueva, Evgenia Spyridonos, and Hanaa Dahy. "Mycomerge: Fabrication of Mycelium-Based Natural Fiber Reinforced Composites on a Rattan Framework." Biomimetics 7, no. 2 (June 2022): 42. https://doi.org/10.3390/biomimetics7020042.

Rapp, Regine. "On Mycohuman Performances: Fungi in Current Artistic Research." Fungal Biology and Biotechnology 6, no. 1 (December 4, 2019): 22. https://doi.org/10.1186/s40694-019-0085-6.

Redaelli, Elena. “Interspecies Collaboration for Woven, Living Megastructures and Fibre-Based Composites in Katya Bryskina’s Research.” ARTEMORBIDA (blog), April 26, 2021. https://www.artemorbida.com/interspecies-collaboration-for-woven-living-megastructures-and-fibre-based-composites-in-katya-bryskinas-research/?lang=en.

Sağlam, Sebahat Sevde, and Seden Acun Özgünler. “An Experimental Study on Production Opportunities of Biocomposite by Using Fungal Mycelium.” Journal of Design for Resilience in Architecture and Planning 3, no. 2 (August 31, 2022): 237–60. https://doi.org/10.47818/DRArch.2022.v3i2056.

Saporta, Shaina, and Matthew Clark. “‘Bio-Welding’ of Mycelium-Based Materials,” n.d.

Scott, Jane, Ben Bridgens, Romy Kaiser, Dilan Ozkan, and Armand Agraviador. “Possibilities of Mycelium Biofabrication in the Built Environment,” n.d.

Scott, Jane, Dilan Ozkan, Aileen Hoenerloh, Romy Kaiser, Armand Agraviador, Ben Bridgens, Emily Birch, Elise Elsacker, and Jane Ozkan. “BIOKNIT BUILDING: STRATEGIES FOR LIVING TEXTILE ARCHITECTURES,” 2022.

Severi, Alessandro. “MyCera | 3D Printing Mycelium Reinforced Structures.” 3D Printers | WASP, September 5, 2023. https://www.3dwasp.com/en/mycera-3d-printing-mycelium-reinforced-structures/.

Sheldrake, Merlin. Entangled Life: How Fungi Make Our Worlds, Change Our Minds & Shape Our Futures. First US edition. New York: Random House, 2020.

Shen, Sabrina C., Nicolas A. Lee, William J. Lockett, Aliai D. Acuil, Hannah B. Gazdus, Branden N. Spitzer, and Markus J. Buehler. “Robust Myco-Composites: A Biocomposite Platform for Versatile Hybrid-Living Materials.” Materials Horizons 11, no. 7 (April 2, 2024): 1689–1703. https://doi.org/10.1039/D3MH01277H.

Snooks, Roland. “Fibrous Assemblages and Behavioral Composites.” In The Funambulist Papers, Volume 1, edited by Léopold Lambert, 164–67. Punctum Books, 2013. https://doi.org/10.2307/jj.2353910.32.

Soh, Eugene, Zhi Yong Chew, Nazanin Saeidi, Alireza Javadian, Dirk Hebel, and Hortense Le Ferrand. “Development of an Extrudable Paste to Build Mycelium-Bound Composites.” Materials & Design 195 (October 1, 2020): 109058. https://doi.org/10.1016/j.matdes.2020.109058.

Soh, Eugene, and Hortense Le Ferrand. “Woodpile Structural Designs to Increase the Stiffness of Mycelium-Bound Composites.” Materials & Design 225 (January 1, 2023): 111530. https://doi.org/10.1016/j.matdes.2022.111530.

Stamets, Paul. Mycelium Running: How Mushrooms Can Help Save the World. Berkeley, Calif: Ten Speed Press, 2005.

Sydor, Maciej, Agata Bonenberg, Beata Doczekalska, and Grzegorz Cofta. “Mycelium-Based Composites in Art, Architecture, and Interior Design: A Review.” Polymers 14, no. 1 (December 31, 2021): 145. https://doi.org/10.3390/polym14010145.

Sydor, Maciej, Grzegorz Cofta, Beata Doczekalska, and Agata Bonenberg. “Fungi in Mycelium-Based Composites: Usage and Recommendations.” Materials 15, no. 18 (September 1, 2022): NA-NA. https://doi.org/10.3390/ma15186283.

Tabellini, Gianluca, Alessio Erioli, Alessandra Zambonelli, Maurizio Montalti, and Philip Ross. “Prof. Alessio Erioli Prof. Alessandra Zambonelli Maurizio Montalti Philip Ross,” n.d.

“Tactical Mycelium 1 & 2 — Jonathan Dessi-Olive.” Accessed May 28, 2024. https://jdovaults.com/Tactical-Mycelium-1-2.

The Growing Pavilion. “Home.” Accessed August 13, 2024. https://thegrowingpavilion.com/.

“The Growing Room in Progress – Follow Our Growing Process in the Newcastle City Centre.” Accessed July 6, 2024. http://bbe.ac.uk/the-growing-room-in-progress-follow-our-growing-process-in-the-newcastle-city-centre/.

"They Grow Without Us | Sala.Ubc.Ca." Accessed September 11, 2023. https://sala.ubc.ca/work/they-grow-without-us.

Watlington, Emily. "Mushrooms as Metaphors." ARTnews.Com (blog), December 29, 2021. https://www.artnews.com/art-in-america/features/mushrooms-as-metaphors-urbonas-studio-tj-shin-xiaojing-jan-1234614585/.

Wiscombe, Tom. "Beyond Assemblies: System Convergence and Multi-Materiality." Bioinspiration & Biomimetics 7, no. 1 (February 2012): 015001. https://doi.org/10.1088/1748-3182/7/1/015001.

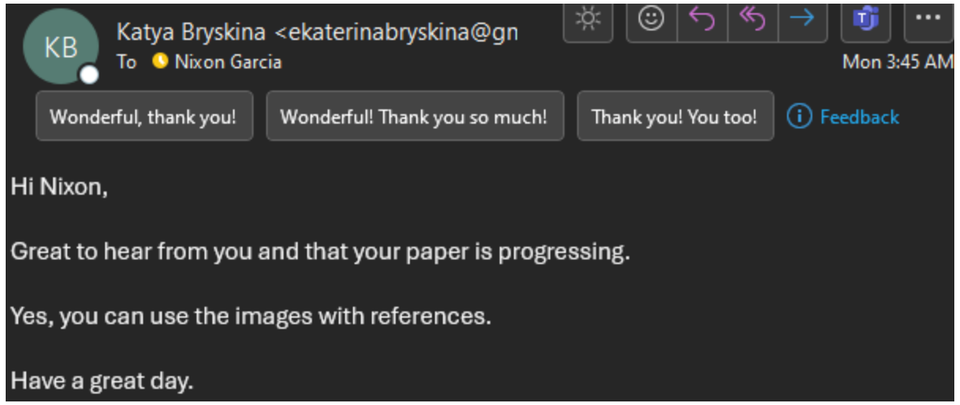
World-Architects. "MycoTree - KIT Karlsruhe + ETH Zürich + Singapore-ETH Centre." Accessed August 13, 2024. https://www.world-architects.com/en/architecture-news/works/mycotree.

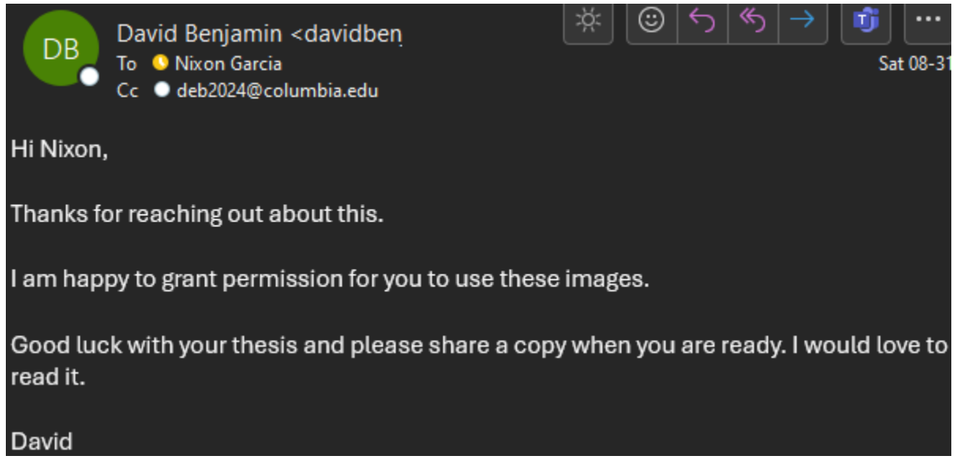
Yang, Libin, Daekwon Park, and Zhao Qin. "Material Function of Mycelium-Based Bio-Composite: A Review." Frontiers in Materials 8 (September 30, 2021). https://doi.org/10.3389/fmats.2021.737377.

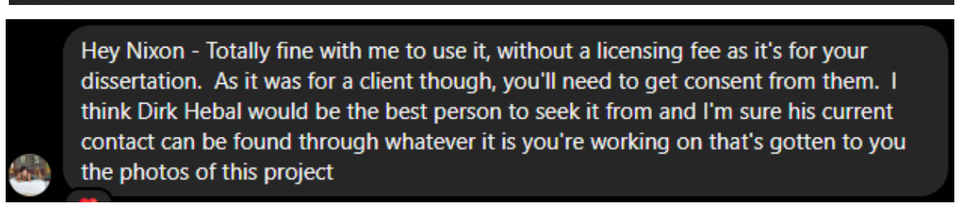
Yogiaman, Christine, Christyasto P. Pambudi, Dhileep Kumar Jayashankar, Peizhi Chia, Yuhan Quek, and Kenneth Tracy. "Knitted Bio-Material Assembly," 58–65. Online and Global, 2020. https://doi.org/10.52842/conf.acadia.2020.1.058.

Zhang, Xijin, Jianying Hu, Xudong Fan, and Xiong Yu. "Naturally Grown Mycelium-Composite as Sustainable Building Insulation Materials." Journal of Cleaner Production 342 (March 15, 2022): 130784. https://doi.org/10.1016/j.jclepro.2022.130784.

Appendix







AA

Armand Agraviador <a.agra

To Nixon Garcia

Cc Jane Scott; Ben Bridgens

Fri 08-30

Hi Nixon,
It's wonderful that you are including our project in your thesis. Hope it all goes well with the writing. And thank you for reaching out to check.

For any image credits, these two photos were taken by Ben Bridgens, copied in. I'm sure they are ok for you to use.

This first Bioknit project had several people involved so best to credit Jane Scott who led it, and the Hub for Biotechnology in the Built Environment (HBBE). The full team list is in the link above for referencing.

Let us know if you have any questions.
Best wishes,

Armand

KG

Kris Graves <krisgraves@gmail.com>

To Nixon Garcia

Tue 11:07 AM

Hello Nixon,

go for it!

peace
+kg

JJ

Julian Jauk <julian.jauk@gmail.com>

To Nixon Garcia

Fri 08-30

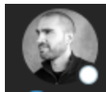
You replied to this message on 2024-08-30 3:02 PM.

Hi Nixon,

glad to hear from you again. Feels free to use our pictures but please make sure to credit them properly (Link to webpage, author: Shapelab (or lost all authors of our paper of my era if you prefer)).

Many thanks for writing! All the best with your paper.

Greetings,
Julian



David Correa

To Nixon Garcia

Fri 08-30

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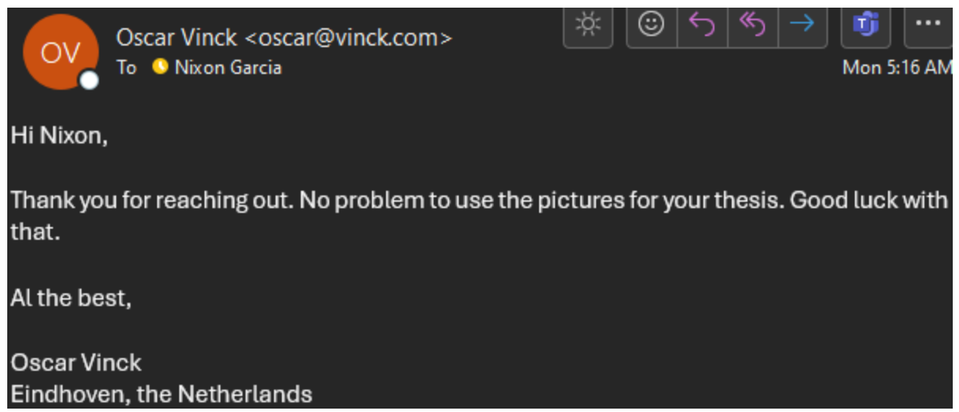
Wonderful, thank you! | Wonderful! Thank you so much! | Thank you so much! | Feedback

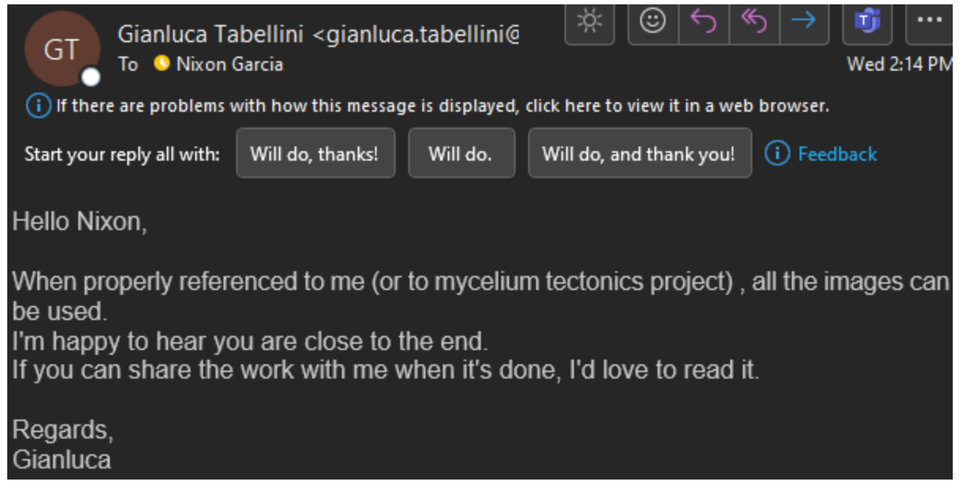
Hi Nixon,

Thank you for asking, you do have my permission to use those images in your thesis.

Best,

David


OV
Oscar Vinck <oscar@vinck.com>
To Nixon Garcia
Mon 5:16 AM
Hi Nixon,
Thank you for reaching out. No problem to use the pictures for your thesis. Good luck with that.
Al the best,
Oscar Vinck
Eindhoven, the Netherlands


GT
Gianluca Tabellini <gianluca.tabellini@
To Nixon Garcia
Wed 2:14 PM
If there are problems with how this message is displayed, click here to view it in a web browser.
Start your reply all with:
Will do, thanks!
Will do.
Will do, and thank you!
Feedback
Hello Nixon,
When properly referenced to me (or to mycelium tectonics project) , all the images can be used.
I'm happy to hear you are close to the end.
If you can share the work with me when it's done, I'd love to read it.
Regards,
Gianluca