Pulp Faction: 3d printed material assemblies through microbial biotransformation

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PULP FACTION
3D PRINTED MATERIAL ASSEMBLIES THROUGH MICROBIAL BIOTRANSFORMATION

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The world is currently facing an ecological crisis of unprecedented scale and urgency and, as the building sector is a significant contributor to the current state, it must look towards radical change to achieve a sustainable practice. The most destructive environmental impact is found in material extraction, processing and discharge. This paper presents an alternative to industrially mined and synthesised materials by utilising biological growth processes as passive engines for the transformation of renewable materials. This is achieved through fungal-lignocellulosic composites which have been developed along with the design and fabrication processes that are necessary for their application in the construction industry.

Plant-derived materials are abundantly and sustainably available on both local and global scales, particularly in the form of by-products and recycled waste. Additive fabrication provides an opportunity to create high value products from this material, but comes with its own challenges. In particular, most of the strength of the wood is lost as fibres are ground down so that the material can pass through the extrusion nozzle. Rather than relying on thermosetting plastics or synthetic binders, this project explores the controlled growth of fungal mycelium within the printed material post-extrusion as a binder of lignocellulosic biomass.

Fungal-lignocellulosic materials inherit properties from both wood and mycelium, resulting in lightweight and strong bio-composites. Generally, they exhibit good insulative performance for both heat and sound, are hydrophobic, and have good tension and compression resistance (Yang et al., 2017; Elsacker, 2019). In addition, the raw materials for such composites are low in cost, locally sourced, renewable, and able to capture and store carbon dioxide.

Mycelium Bio-Composites

The main components of mycelium composites are the biopolymers cellulose and chitin, followed by lignin and hemicellulose. Mycelium is the vegetative part of a fungus, made up from a dense network of long, branching filamentous structures termed hyphae. The cell wall of the hyphae is made of chitin – a tough, resilient, inert and non-water-soluble modified polysaccharide that has promising potential in biotechnology (Latgé and Calderon, 2006). When the fungus colonises a substrate, it first grows on the surface and gradually, depending on

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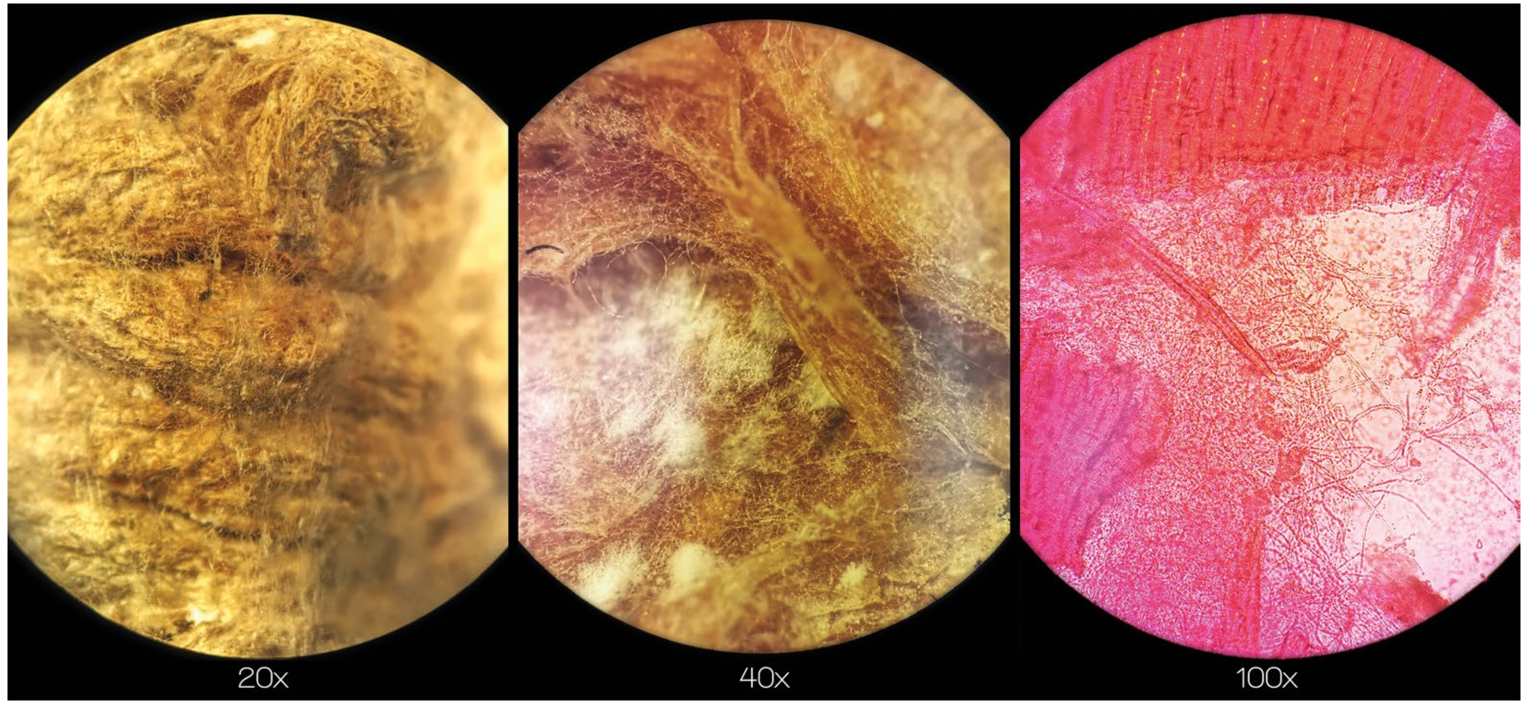

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1. Section of a column showing an assembly of the fungal-lignocellulosic components. Bonding between the segments is proposed to be achieved by extrusion of a connective tissue consisting of a modified version of the live pulp.

2. Substrate under microscope. The different magnifications showing: (1) The print layers covered in mycelium. (2) The fusion of mycelium and substrate. (3) The partial decomposition of the cellulose and lignin fibres by the fungus.

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3. *Termitomyces* fungus comb. This symbiotic structure is additively assembled by macrotermites from dead plant matter inoculated with fungal spores. The fungus slowly digests the plant matter into components which the termites can ingest as food, while it simultaneously acts to regulate the humidity of the mound's internal climate.

4. Living printed composite after two weeks of incubation.

the properties of the material, it spreads its mycelium throughout it in a complex three-dimensional binding matrix (Boyce and Andrianopoulos, 2006) (Fig. 4). During growth, the fungus secretes extracellular polymeric substances (EPS), which are mainly composed of polysaccharides and proteins (Gazzé et al., 2013). Their role is to facilitate growth and allow the anchoring of the cells on the substrate, acting as a glue between the hyphae and the substrate. Moreover, EPS allow for the conglomeration of particles around the hyphae, resulting in an irreversible fusing of the material (Fig. 2).

3D Bio-Printing

Most precedents using lignocellulosic substrate and mycelial growth for creating bio-composites use casting as the means of production, for example: The Living's Hy-Fi Tower (Nagy et al., 2015); Block Research Group's MycoTree (Heisel et al., 2018); Mogu panels (Appels et al., 2019). Such methods are relatively straightforward and therefore well-suited for industrial mass-production. However, the casting process limits the customisation of the products as well as geometrical complexity that can be employed for functional performance. In addition, the strength of the material is markedly determined by the extent of the mycelium coverage (Yang et al., 2017). As this is dependent on oxygen, growth is limited to the material surface. When cast in solid volume, the mycelium covers a smaller percentage of the total volume, limiting the potential strength of the composite.

These limitations can be overcome through the use of digital additive fabrication which allows for a complex meso-scale structure, radically increasing the surface area within a given volume and thus ensuring maximum distribution of hyphae within the composite.

The strategy of additively fabricating mycelium composites is not unprecedented in nature. Mound-building macrotermites have evolved to a symbiotic existence together with fungus of the genus *Termitomyces*. The termites harvest plant-based material and carry it back to the mound where the regulated internal climate is suitable for fungi. The fungus processes the plant matter, turning it into nutrients that both the termites and fungus live on (Turner, 2005). The fungal combs (Fig. 3) have a particular geometry which, on the one hand provides access to the termites for managing the comb, and on the other enable a convective flow of air and respiratory gases near the comb surfaces. This flow is facilitated by vertical channels and assisted by the thermal buoyancy generated by the metabolic heat of the fungus. The combs are constructed as an intricately folded and interconnected sheet with an even thickness of approximately 4mm, likely corresponding to the depth at which the mycelium can effectively grow while maintaining access to oxygen. The fungus comb provided an initial set of assumptions for a design that could provide a suitable balance of parameters in the project.

Integrated Research Protocols

The research presented in this article concerns the finding of a set of processes for additive fabrication of fungal-lignocellulosic materials and the evaluation of their suitability for architectural fabrication. The primary intent was to address the questions that arise from the interdependencies between these processes through a transdisciplinary approach. Focus has been on testing feasibility, building a protocol, and establishing a foundation for informed speculation.

The research was guided by the following questions: How can a process of bio-fabrication best be structured to achieve desirable artefacts? How does the introduction of fungal mycelium affect the material properties? And how could the developed processes be utilised for fabrication at architectural scales?

To answer these questions, the presented work explored the interconnections between (1) the living system, (2) the digital fabrication, and (3) the computational design strategy. Subsequently, a number of material performance tests were carried out on the resulting samples. The protocol presented here led to the most successful outcomes with regards to rate of growth, extrudability, stability and resulting material properties.

Live Pulp

The pulp consists of a substrate that has been inoculated with fungus. The substrate was developed to comply with two primary criteria: its ability to support the growth and development of the fungus, and its suitability for fabrication which includes both extrudability and the stability of the material in the print and growth phases. The main components of the substrate are fine woodchips, paper pulp, and kaolin clay, which are mixed with water. Wood and paper pulp compose the bulk of the material and provide the nutrients for the fungus; during incubation, these are partially transformed into fungal biomass. As the substrate doesn't have an immediate bonding agent, it remains unstable during printing. Therefore, clay was added to the mixture to provide stability during the fabrication and incubation phases. The substrate also contains a thickening agent which allows the solid and liquid components to form a coherent aggregate (Fig. 10).

Two fungal strains were used in the experiments, a strain of *Byssomerulius corium* and a strain of *Gloeophyllum* sp. They are both wood decomposers, but follow different strategies of wood decomposition termed white rot and brown rot, respectively. Both fungal strains were propagated on a malt-yeast medium. When the mycelial growth was sufficient, the fungus was introduced into the autoclaved substrate. The inoculated substrate was left for an incubation period of one week, in which the mycelium propagated through the substrate and adapted to the new environment, enabling it to resist contaminants introduced when sterile conditions were no longer maintained.

Following the initial incubation, the pulp was 3D printed, after which it went through a second and longer incubation period. This allowed the mycelium to grow through the printed artefacts and transform the substrate into the desired bio-composite. Once the growth had reached the target state, the printed component was desiccated to reach its final and stable form, stopping the decomposition process.

Fabrication Strategy

The live pulp was 3D printed using Vormvrij Lutum v4, which relies on a combination of pressurised air and a rotating auger to extrude material. A nozzle diameter of 3.5mm was used in combination with a layer height of 1.5mm, which provided a working balance of resolution, stability, and print speed.

Several factors influence the stability of the print, and the ability to produce artefacts with the desired geometric variation. A larger nozzle and consequently greater wall thickness make for more stable prints, but have the drawback of lower resolution and decrease in surface to volume ratio, which reduces the amount of mycelial growth on the material. Straight vertical walls are prone to both deformation and collapse. To reduce this, the curvatures have been maximised and additional interconnections between walls were introduced.

During desiccation, the material contracts in volume by approximately 30%. In order to minimise the resulting distortion, a set of aluminium meshes with vertical channels were used as print base and cover. These secure the position of the first and last layers, thereby constraining the contraction to the Z-axis. Mesh-print adhesion was improved by the explorative growth of the mycelium. The meshes allow vertical airflows through the print, supporting biological growth by ensuring even moisture levels and the circulation of respiratory gases, and eventually facilitate rapid and even desiccation.

Design Strategy

In addition to the architectural scale constraints, the design of the components had to accommodate both the biological requirements of the fungus and the mechanical constraints of the printing process. A reaction-diffusion simulation based on the the Gray-Scott model generated the basis for the form-finding of the fabricated geometries. The scale of the pattern was derived from the fungus comb reference. This generative model has been developed by increasing the feed rate along the vertical axis. The boundaries of the geometry have been created at the transition points between the two simulated substances. Subsequently, the resulting geometry consists of two (internal and external) interwoven volumes that never converge, lending itself to functional use in the architectural outcome. Similar to the structure found in fungus combs, the model ensures significant vertical continuity that is beneficial to flows of both air and structural forces. (Fig. 5)

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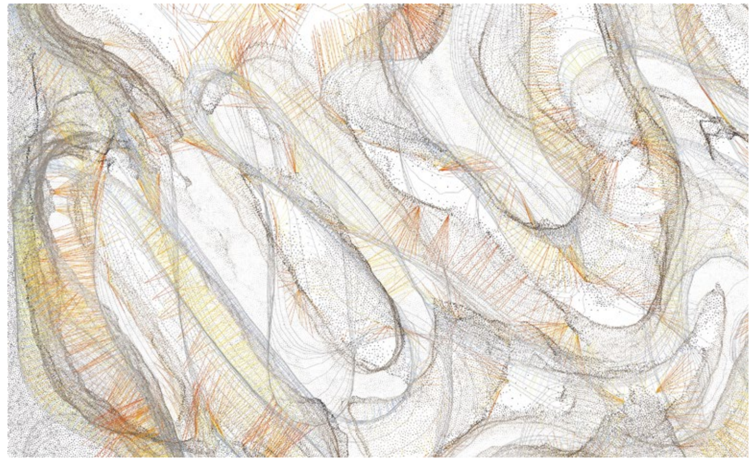

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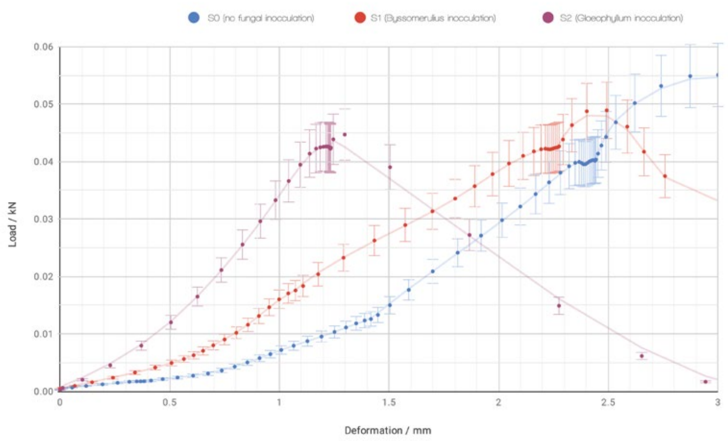

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5. Column assemblage: design to fabrication.

6. Dessicated printed sample comparison. From left: S1, S0, S2.

7. Detail of the 3D scanned prototype. Analysis of deviation from the toolpath sent for fabrication, after printing, growth and desiccation. Although there is considerable distortion, it is locally distributed throughout the height of each module and therefore not global, the tolerances not penalising the current design application.

8. Mechanical performance: bending test.

The curves that constitute the print layers are taken through a secondary algorithmic transformation which connects all curves into a single curve on a per-layer basis. This transformation allows for a continuous extrusion rate along an uninterrupted toolpath which improves speed, stability and precision in the print process. This also ensures that the entire printed component is cohesive and that additional stabilising cross-bracings are created without disturbing the continuity and separation of the two sets of volumes. In order to maintain thin extrusions while increasing the print height, the design strategy combined vertical continuity with recurring interconnections, while strengthening through double curvature.

Results

Three different material samples (designated *S0*, *S1*, and *S2*) were tested for the resulting material properties and their suitability for architectural application. S0 was printed substrate with no fungal inoculation, S1 was pulp with the fungal species *Byssomerulius corium*, and S2 was pulp with a *Gloeophyllum* sp. (Fig. 6). Three tests were carried out: a bending test to evaluate stiffness, a test for dispersion in water, and a test for water absorption properties. Since the results from these tests indicated that the *Gloeophyllum* pulp composite has the most desirable properties, additional samples were produced and further scanned to characterise the distortion of the material during drying (Fig. 7). This is notable since most other mycelium-based materials use white rot fungus, while here is was found that the brown rot fungus, *Gloeophyllum*, gave the better result.

Mechanical Performance

The bending test showed that the samples with more extensive hyphae distribution exhibited significantly higher stiffness than the mycelium-free sample and afforded a slightly higher force before failure (Fig. 8). The deformation before failure was twice as high for S0 as S2, with S1 falling in between. The hardness of the material as perceived when cutting the samples with a sharp knife was significantly higher with increased hyphae coverage (S2 > S1 > S0).

Dispersion in Water

The resilience of the material bond when wet was tested by submerging the samples in water for a period of 10 hours. After this period, the water and samples were stirred (Fig. 9). The sample without mycelium (S0) quickly swelled and completely disintegrated upon agitation. S1 and S2 remained intact during stirring.

Hydrophobicity

A droplet of water was placed on each of the surfaces of the three samples, and the subsequent absorption was observed. The droplets on S0 and S1 were quickly absorbed, while the droplet placed on S2 did not absorb but maintained its shape, indicating strong hydrophobicity on the material surface (Fig. 11). The samples' capacity for buffering water in vapour form was also measured, and remained equally high in all three samples.

The printed prototypes and tests conducted on the resulting bio-composite demonstrate some of the advantages of the proposed approach. The resulting components were highly hydrophobic with a retained capacity of moisture buffering, and remained stable even when exposed to prolonged submersion in water. The transformation of the material by the fungus resulted in improved stiffness and hardness, and eliminated the tendency of the samples to delaminate between printed layers. The surface hardness of the resulting material was markedly different from many other reported mycelium-based materials. This may be due to the use of a brown rot fungus instead of white rot, and this strain's interaction with the substrate. However, further studies are required to investigate these relationships.

The ability to fabricate larger scale elements relies on navigating the requirements in the design space, and the stability and predictability of the printed components in the growth and desiccation phases. The robustness of the process was improved by the inclusion of clay to the substrate as well as the use of stabilising meshes. Equally, the component design is of critical significance, both in terms of enabling the growth of the mycelium and stabilising the material during and after fabrication. This resulted in a requirement for a high surface area, high curvature form.

When engaging with the agency of microorganisms as well as with highly responsive and interdependent materials, significant constraints are placed on the design. These constraints require integration between the multiple scales of the project, from the microscopic scale of microbial behaviour, through the material arrangement at the centimetre scale, all the way to the component and assembly, and eventually human scales. Rather than considering these constraints as limitations, they present an opportunity for responsive and functional architectures.

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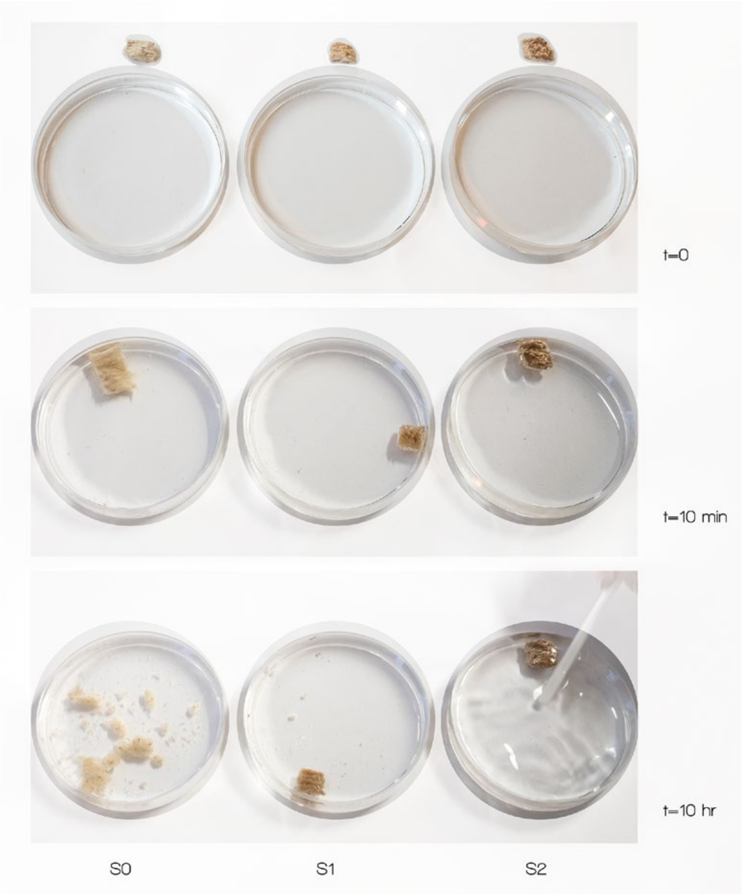

9. Dispersion in water. The fungus-free sample disintegrates completely, while the two fungal composites exhibit minimal swelling and remain intact after stirring.

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10. Substrate development prototype, here without fungus. The substrate was tested for extrudability, as well as for the design – material compatibility.

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11. Hydrophobicity. From left: S0, S1, S2.

The demonstrated components (Fig. 1) assemble into a column that retains several of the properties that allow the fungus to thrive: it has a high surface area ratio, the vertical interstitial spaces allow for convective flow, and the material exhibits an active interaction with air and water vapour. These properties remain after the element is constructed, and can be utilised to affect and modulate the environment in direct proximity to the column. Rather than a passive load-carrying element, such a structure should be considered a part of a building's vascular system, mediating and enabling flows that drive an active modulation of the micro-climates which the occupants inhabit.

Conclusion

The project demonstrates both the challenges and the potential of additive fabrication of mycelium composites. The introduction of fungus improves the properties of the resulting material in multiple ways, resolving difficulties associated with wood printing through improved water resistance and increased stiffness and hardness. Compared to previous fungus composites which are typically fabricated through casting, additive fabrication can improve the conditions for fungus growth, enabling faster growth rates and more complete coverage. This can result in better material performance and more efficient manufacturing. The process enables complex and customised form beyond what can be achieved through casting, opening up new functional potential in the resulting products.

The biologically active process adds constraints, such as the need for sterile material processing and the prolonged wet state. However, it was demonstrated how a combination of material composition, design integration and fabrication processes can be used to overcome these challenges, potentially enabling the use of such materials in the construction industry. If implemented at large scales, such a shift could radically reduce the building industry's ecological footprint by lessening the need for extraction of non-renewable minerals and for energy intense chemical processing, while ensuring environmentally safe and biodegradable properties.

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References

Appels, F.V.W., Camere, S., Montalti, M., Karana, E., Jansen, K.M.B., Dijksterhuis, J., Krijgsheld, P. and Wösten, H.A. 2019. 'Fabrication factors influencing mechanical, moisture- and water-related properties of mycelium-based composites', *Materials & Design,* 161, pp. 64-71.

Boyce, K.J. and Andrianopoulos, A. 2006. 'Morphogenesis: Control of Cell Types and Shape', in Kües U., Fischer R. (eds), *Growth, Differentiation and Sexuality vol 1: The Mycota (A Comprehensive Treatise on Fungi as Experimental Systems for Basic and Applied Research)*, Berlin, Heidelberg: Springer, pp. 3-20.

Elsacker, E., Vandelook, S., Brancart, J., Peeters, E. and De Laet, L. 2019. 'Mechanical, physical and chemical characterisation of mycelium-based composites with different types of lignocellulosic substrates', *PLoS ONE* 14(7), p. e0213954. (doi: 10.1371/journal.pone.0213954)

Gazzè, S.A., Saccone, L., Smits, M.M., Duran, A.L., Leake, J.R., Banwart, S.A., Ragnarsdottir, K.V. and McMaster, T.J. 2013. 'Nanoscale Observations of Extracellular Polymeric Substances Deposition on Phyllosilicates by an Ectomycorrhizal Fungus', *Geomicrobiology Journal*, 30(8), pp. 721-730.

Heisel, F., Lee, J., Schlesier, K., Rippmann, M., Saeidi, N., Javadian, A., Nugroho, A., Mele, T., Block, P. and Hebel, D. 2018. 'Design, Cultivation and Application of Load-Bearing Mycelium Components: The MycoTree at the 2017 Seoul Biennale of Architecture and Urbanism', *International Journal of Sustainable Energy Development*, 6(1), pp. 296-303.

Latgé, J. P. and Calderone, R. 2006. 'The Fungal Cell Wall', in Kües U., Fischer R. (eds), *Growth, Differentiation and Sexuality vol 1: The Mycota (A Comprehensive Treatise on Fungi as Experimental Systems for Basic and Applied Research)*, Berlin, Heidelberg: Springer, pp. 73-104.

Nagy, D., Locke, J. and Benjamin, D. 2015. 'Computational Brick Stacking for Constructing Free-Form Structures', in Thomsen M., Tamke M., Gengnagel C., Faircloth B. and Scheurer F. (eds), *Modelling Behaviou*r, Cham: Springer, p. 203-212.

Turner, J. S. 2005. 'Extended physiology of an insect-built structure', *American Entomologist*, 51(1), pp. 36–38.

Yang, Z., Zhang, F., Still, B., White, M. and Amstislavski, P. 2017. 'Physical and Mechanical Properties of Fungal Mycelium-Based Biofoam', *Journal of Materials in Civil Engineering*, 29(7). (doi: 10.1061/(ASCE)MT.1943-5533.0001866)