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ORIGINAL PAPER

Mycostructures—growth-driven fabrication processes for architectural elements from mycelium composites

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Abstract

The paper discusses how characteristics of the mycelium growth process—namely different growth effectiveness depending on the nutrition content of the substrate, gradual solidification of the inoculated substrate, and bio-welding—can be a driving force for developing sustainable biofabrication processes of mycelium based composites (MBC) for architectural application. To explore this potential one-semester (12 weeks) seminar and one block seminar (2 weeks) with master-level students were held at the University of Stuttgart, and independent work within the Institute IBK2 was performed. The free experimentation with fabrication tactics resulted in the emergence of different investigation paths, tested with small-scale demonstrators, from which the most interesting three this paper presents in detail. The first is the two-phase printing process of mycelium substrate and subsidiary reusable support materials. It applied tests with the small, inorganic, loose substances (plastic pellets) extractable mechanically and meltable substances (wax) extracted by heating. The second path of investigation followed lost formworks created from hemp strings positioned inside the material. Finally, the third path is a particular case of lost formwork approach utilizing different tubular bandages stuffed with MBC and utilizing it later as a thick filament for other different form-giving deposition practices: layering, hanging, braiding, and knotting. All three investigation paths prove feasible, although their upscaling potential correlates strongly with the successful automation of the processes using CNC machines, which could provide the precision and sterility needed for this highly heterogenous and sensitive material. In addition, further developments in the material cultivation protocols are indispensable to provide a higher repetition of the results.

Keywords Mycelium · Mycelium composites · Biomaterials · Biocomposites · Biofabrication · Circular design

Introduction

In recent years, the need to reduce the construction industry's carbon footprint has pushed many architects to rethink the materiality of designed buildings. It is done either by looking into the regenerative materials traditionally employed in vernacular architecture or by trying to adapt them to the needs of contemporary construction. The works mainly focus on mainstreaming wood and its engineered products (CLT, fiberboards). Other materials like strawbale, reet, cork, and rammed earth are used sporadically, and their influence on market change can be considered neglectable. The different path is paved by exploring new materials with a low carbon footprint, which traditionally has not been applied in construction.

One of the forerunners of such explorations are mycelium-based composites (MBCs). MBCs are gaining momentum in recent years, with an increased number of publications appearing each year [1, 2]

Production of the material using fungi is researched in many fields of application. Flexible fungal materials (utilizing either fruiting bodies of fungi or pure mycelium are finding their way as fungal leather, foams, or paper-like materials [3]. MBCs, combining fungal mycelium and lignocellulosic fibers originating from waste streams, resulting in different characteristics than FFMs, are more suitable for targeting applications in design and architecture [4]. The progress in the research of MBCs is tightly connected with the

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understanding of all the frameworks related to the production of these materials (choice of fungal specie, feedstock, sterilization, inoculation, packing, growth conditions, time, drying, post-processing, application) and input factors influencing each stage, and impact which they can have on the end material [5]. As the number of variables is immense and crosses different disciplines (microbiology, biotechnology, material science, material engineering, architecture, design), the progress in getting accurate results and showing precise interdependencies is challenging. In addition, the lack of production [5] and testing standards for material physical properties [6] developed for MBCs, makes it difficult to compare the results between different publications unequivocally. For example, in the recent review article by Aiduang et al. [6], the compressive strength values were reported for 31 different MBCs, with 15 providing no test standard and the remaining 16 utilising eight different standards.

One of the gaps in knowledge that could be filled relates to sustainable production methods and developing a new aesthetic design language for MBC [4]. Due to limited infrastructure and possibilities for interdisciplinary collaboration, it is the aspect on which we decided to focus in the study.

Goal of the research

This paper sets out to document and assess methods and the results of a series of integrated design-to-biofabrication experiments. These took place at the Institute for Building Construction, Technology and Design, Chair 2 (IBK2) at the University of Stuttgart during the seminars Building Systems: Mycostructure (12 weeks of winter semester 2020/2021, 10 students, master level), Myzelpavillion (2 weeks of summer semester 2020, 1 student, master level) and during the independent work in the institute.

Design intentions were channeled towards developing a building system demonstrating the free-forming potential of additive manufacturing of mycelium composites. Therefore, the load-bearing situations were targeted. Students were asked to withdraw the usage of custom-made polypropylene molds and look for an alternative procedural path that incorporates either no-waste or only bio-based materials that could biodegrade with mycelium. The driving force for the design of the fabrication procedures was the requirements of the mycelium growth process. Such processes differentiate the formation of mycelium composites from the other composites in the building industry, which are based on purely chemical processes involving petrochemical-based resin matrices. The involvement of the microorganisms opens up new procedural possibilities, thanks to form-related variables present in the process: air penetration depths, transpiration, and moisture preservation potential. The investigation targets those variables as they are the most design related and can profit the most from the design-research investigation process. Contrarily, the substrate compositions and cultivation protocols are inherently linked to the microbiological aspect of investigations, which are hard to realize without the laboratory setting, which was not available for us during that time.

The research intended to comprehend whether a non-conventional fabrication process can bring advantages under aesthetic (i.e. extending a design space of architectural form, aiming for unique spatial and material experiences) and practical criteria (i.e., economy of material, structural integrity, 'strong-by-form' formation potential). The investigation's experimental and explorative character targets testing the methods' feasibility, establishing fabrication protocols, and building foundations for more informed speculations.

Background

The recent construction of multiple MBC structures allows for naming emerging methodological directions. The detailed analysis of the projects below tries to gather the methodologies and simultaneously indicate the relations between the design variables originating in the material qualities of MBC and form-giving processes. Cited examples vary in scale, but all of them target the architectural context of the application.

Recreation of archetypical elements' forms 'substituting the materiality'

The first approach is the recreation of the archetypical units of construction, namely bricks and plates, and assembling them using proofed and well-known construction methods. This allowed for reducing the number of unknown variables in the construction process to the sheer minimum and observing how the building elements will behave when subject to substituted materiality. Furthermore, this approach allowed for the construction of the largest prototypical structures to date.

The first example, utilising MBC bricks, was the 'Hy-Fi', created as a temporary structure for the MoMA PS1 pavilion program, constructed in 2014. Bricks were cultivated before the assembly process, utilising impermeable polypropylene moulds. They were later assembled into the curved walls, connecting into the melted-together trifold hollow tower, reaching around 12 m in height. The curvature of the walls contributed to the overall stiffness of the structure. However, the wooden support frame with steel cables was still needed to provide the necessary safety under the wind load condition and, on the other, to provide guides during the bricks stacking process. Bricks were connected by the traditional mortar (Hydrocrete) and chopsticks to provide additional mechanical shear force connection [7]. One-layer brick stacking and taking advantage of the curvature for structural stability were historically only applied on rare occasions. The best-known example is crinkle-crankle walls in Suffolk, England (REF), constructed for the plot divisions. Therefore, the project can be considered a particular inspiration of the masonry constructing techniques merged with the hybrid support system for creating unusual, sculptural space. The unusual form, addressed the aspect of the myco-bricks, being a weak material and needing to take advantage of the stability-through-form. However, the architecture aimed predominantly at creating a spectacular spatial effect, well suited for introducing the new material to the general public, then for creating the universal construction system.

An example utilising MCB plates at facade panels is 'The Growing Pavillion' [8], where the panels are mounted vertically, as the outer facade of the cylinder-like, ground-floor pavilion constructed with the use of different biomaterials. The panels are mounted directly to the timber frame load-bearing structure. Analogously, mycelium panels covered shell like-structures: created from timber members in "Shell Mycelium" in India [9]. The ring-like panels were in the pavilion at the Rensselaer Polytechnique Institute, Troy, NY, USA [10], tight together and positioned between the wooden frames creating a doubly curved surface. In the Urban Mining and Recycling (UMAR) unit in the research building NEST of the Swiss Federal Materials Testing and Research Institute, MBC plates were utilised as insulation boards, without direct contact with the outside surfaces. Therefore in the visual perception of the building, they are not present [11].

A bit particular case is the panels utilised in the MY-CO SPACE pavilion in Frankfurt am Main, Germany were composites created by growing together the layer of myco-material and plywood. They were attached later to milled plywood ribs giving form to the whole pavilion space [12]. The mentioned thickness of the panels (4,5 cm) allows for speculation that in such an application, plywood could accommodate all the forces acting on the pavilion skin, taking away the risk of the project's stability from the physical properties of the utilised MBC.

The listed applications of the MCB plates are inherently not load-bearing. Their use in the projects aimed at the feasibility showcase of the new material on an architectural scale. The applied forms were simple and did not create challenges for the moulding process. The material properties that were taken advantage of were thermal insulation properties (UMAR), surface quality, and aesthetics (mentioned Indian and American pavilions).

Custom discrete blocks with integrated joining systems—hybrid materiality

Another emerging methodological direction is the application of custom-made discrete blocks developed in the process of informed structural engineering and form-finding, which may be related to the discipline of stereotomy in the history of architecture [13]. The possibility of casting the loose substrate in custom-made moulds is paired with the need to develop a custom join system. Joints allow for the precise orientation of blocks to one another and are the stay-in part of the mould, facilitating the proper stuffing of the inoculated substrate.

In the MycoTree project, MBC blocs form a three-meter-high funicular branching structure carrying four by four-meter bamboo grid acting as a tensioning element for the ends of the branches. The blocks are finished with bamboo composite plates with dowels grown together with the myco-material [14].

Another project of the category is Mycocreate 2.0 is a small, branching, prototypological structure (fitting within a bounding box of 2.6 × 2.1 × 1.6 m) consisting of 64 unique MBC block components. Each of the blocks finishes with acrylic end plates, connected by an inner guiding strap going through the inside of the respective block [15].

Both projects rely strongly on elaborate moulds. In the case of Mycocreate 2.0, reaching the proper workability of the utilised inoculated substrate in conjunction with the moulds is thematised as the key factor allowing to pursue this methodological direction [15]. However, the experiments of Elsacker et al. [16] with robotic abrasive wire cutting allow us to speculate that this design methodology can profit from this substructive approach. The blocks can be cultivated as generic specimens, then bright to form by robotically cutting living material and then incubating it to create outer mycelial skin. The subtracted living material can serve as a spawn for further material cultivation. This approach would also eliminate the need for elaborate moulds. The two-stage fabrication process for MBC is also elaborated in the review by Bitting et al. [17].

Monolithic in-situ casting

MCB are often praised as the only bio-based material which allow for casting. However, it biological process of solidification differs in it's demands from the widespread methodes of widespread in-situ concrete casting. In the project Monolito Micelio students of Georgia Institute of Technology aimed at testing the relationship between MCBs and in-situ casting. They developed the small 2,5 × 2,5 × 2,5 m pavilion whose form originated from splitting a funicular column into four parts and assembling them back together as a symmetrical, four legged vault shell inscribed in a cube. The project utilised CNC milled oriented strand-board (OSB) as the internal lost-formwork and the plywood and nylon geotextile as the external formwork [18]. Project withstand 3 months during which it developed cracting and decay resulting from the different contraction rates of the main MCB material matrix and OSB reinforcement [19].

In Monolito Mycelio project the lost formwork was CNC milled and situated in a way that didn't influence the targeted, 3d modeled geometry. It is the typical case in internal reinforcement of architectural elements—reinforcing elements are situated internal, hence not visible and not 'compromising' the targeted form.

Monolithic casting with visible reinforcing lost formworks

The other approach was taken in the projects, which thematised the lost formwork as a vital element of form-giving practice. In the works of consortium FUNGAR the kagome 3-axial weaving technique of wooden stripes is developped as the leverage for the MCB casting on double curved surfaces [20]. Project Mycomerge, which tested the feasibility of building funicular shell structures from MCBs facilitated by the lost formwork of rattan, hemp sheets and hemp fibers. The traces of ratan orientation are well visible on the exterior of the piece. The resulting test-component in form of a funicular stool was able to withstand 20 times it weight without visible deformation [21]. The Students of Kansas State University developed the 2-m tall column from MCB casted inside the exosceleton weaved using basket-making techniques. The reinforcing potential of this weaved surface is assumed due to over growing of the surface with mycelial skin and merging of two entities [19]. Also the fundamental research work of Özdemir [22] bears the inclination to this form giving methodology by investigating the influence of maple veneer stripes in forms of 2d and 3d lattices as the reinforcement of MCBs.

Traditionally in crafts, soft and flexible plant-based materials (wicker, rattan, timber stripes, staw) were used to create complex 3d forms of everyday objects and decorations. The experimental projects mentioned in the last paragraph can be therefore perceived as an attempt to bring up this crafts heritage into the contemporary realm and discourse of modern, bio-based, bio-degradable and sustainable architecture. Applying the bio-materials in permeable form as a lost formwork doesn't compromise air penetration into the MCB and the biodegradability of the resultant pieces.

Monolithic casting and lost formworks—case of textiles

The application of the textile as a formwork was investigated in Knitted Bio-Material Assembly [23]. The project utilised pre-tensioned 3d woven textile tubes to cast MBCs. Different materials (cotton, acrylic and ultra-high molecular weight polyethylene—UHMWPE) of yarn influencing the growth effectiveness of MCBs were tested and compared.

The BioKnit pavilion is the biggest up-to-date MCB structure utilising textiles as the formwork for MCB. It is created as a branching dome, 2-m diameter and 1,8-m high. It was grown upside down, taking advantage of the material computation of optimal form through hanging chain principle. The scaffold fabric is knitted with linen-wool yarns. Except for fungi, it also employs bacterial cellulose for the semi-transparent parts of the structure [24].

The structure L'Orso Fungino grown by K-State students was the wall unit, grown in the textile formwork from the synthetic geotextile tensioned on the frame created from the timber members, CNC-cut plywood panels and plastic laminates. The units were around 75 × 75 cm big, with undulating ruled geometry. Inside of the casted wall, aeration ducts from perforated cardboard pipes were placed, to allow better aeration of MCB during the growth phase. After drying the pieces, the ducts also served as canals for the post-tensioning rods, assembling two wall units [19].

Due to the small opening in the textile's surface, the mycelium grows through it and merges with it. It can be dried together and stay as joined indefinitely, or it can be torn away at the end of the cultivation phase. The textiles can be sawn into formworks, but can also be directly 3d knitted into desirable 3d forms. The whole discipline of textile and fibre engineering studies how different yarn's organisation and materialities translate into the properties of the overall materials. The interaction between textiles and living organisms like mycelium is a relatively new field. However, its development can be observed with attention as it, on one hand, can draw from the very interdisciplinary body of knowledge and on the other can lead to the development of optimised, smooth and original architectural design space.

Bio-welding as the leverage for mono-material assembly

The 'brick and mortar' approach was explored in Growable Architecture [25], where bricks and mortar paste shared the same composition and were applied with the time offset. This experiment directly translated the masonry construction technique into the new material case. However, this approach worked to a limited extent and, due to contamination cases, was not explored fully and required further work. Dahmen also reported a similar experiment—mycelium brick bio-welded into one piece of the wall installation called 'Mycelium Mockup'[26].

The two exhibitions pieces created by The Living, namely Living Bricks [27] and Voxel Bio-Welding and Jammed Bio-Welding [28] demonstrated the potential of small blocks made out of mycelium material to bind together or in other words—grow their mortar. In both installations, mycelium cylinders were amassed in the temporary scaffolding to aggregate into the structural arch,then, they got additional nutrients to boost their growth. In the end, the scaffold was disassembled, leaving the structure self-supporting [29, 27]. Unfortunately, this exploration lacks a full process record beyond the short press notes and abstract.

Bio-welding, the ability of pre-grown thick plates to join together, were used to create big-scale mycelium blocks in the experiments of Elsacker et al. [16]. It successfully created homogeneous blocks and overcame the obstacle of limited air penetration in the growth phase.

The structure La Parete Fungina grown by UVA students consisted of undulating stripes of MCB stacked on top of each other during the second growth phase to allow for bio-welding. It resulted in the 1,2-m hight undulating wall, which, when exhibited in outside conditions, withstood the snow and wind without damage [19].

Bio-welding as the vital process of material assembly was thematised in the Bio-Ex Machina 3D printing experiments of Co-De-It and Officina Corpuscoli [30] and also explored more detail in 3d-printing experiment PulpFaction [31]. In both cases, the mycelium elements which bio-welded together were continuous filaments, a few millimetres in diameter, positioned exactly with a robotic arm and 3d-printing end effector. However, by adding the clay in Pulp Faction experiments, the filament's lack of stability and immediate bonding agent was overcome. In contrast, in Bio-Ex Machina, the composition of the filament was not specified.

Experiments with custom fabrication: Methodes and findings

As the material properties of mycelium composites can significantly vary depending on the substrate composition, all the initial tests started with the same bulk material, irrespective of the chosen path. The pre-grown inoculated subtract Grow-It-Yourself pack was purchased from the company Grown. In each set of the investigations, the inoculated substrate was mixed with the wheat flour in proportion (500 g substrate/50 g flour).

Experiments led to the emergence of 3 distinctive paths of investigation, where the mycelium growth process is a driving force for developing sustainable biofabrication processes of mycelium composites for architectural application. There were, respectively: different growth effectiveness depending on the nutrition content of the substrate (two-phase printing), gradual solidification of the inoculated substrate (lost formwork from an inner scaffold), and bio-welding (tubular bandage facilitated filaments).

More small-scale demonstrators were created than presented in the paper. However, many were not fully grown, caught mold, and did not reach the desired stability and form. Omitted demonstrators belong to lost formwork (hand-sewn cotton fabric textile formwork and inner scaffolds from different strings) and thick bandage-facilitated filaments (filament weaving).

Path 1: Two-phase printing

The designed piece was sliced into 1 cm thick layers, and the boundaries of each layer were mapped using a projector. This way the substrate and support material could be deposited manually, layer by layer in a 5L plastic container. The initial test were made with the provided material, however they momentarily showed that the viscosity of the mix is insufficient. Therefore, the new material composition was made, consisting of: inoculated substrate (92%) with 3% of wheat flour and 5% of psyllium husk previously mixed with water.

Plastic granulates support material

The support material was plastic gravel balls of 2 mm diameters. The container filled with layers was sealed and the growth process was observed.

In the first 7 days the speed of the growth process was below expectations. Consequently, the number of air holes in the container was increased which resulted in faster growth of mycelium structure. The piece was removed from the bucket after 14 days but the growth process itself has not stopped yet.

Although mycelium roots did not grow through plastic itself, it managed to grow through air gaps between plastic granulates, forming relatively weak connections. Consequently, the granulate had to be removed by delicate carving rather than falling apart itself.

It was observed that mycelium rooting deep inside the piece was not as well developed as on the outside, probably due to lack of air. For that reason, after removing part of the granulate support, it was left for further growth for another 7 days. Finally, the growth process was stopped by drying the sample in 80 °C for 8 h. The quality of the resulting piece was tested by compressing it with 70 kg of distributed load numerous times. No elastic or plastic deformations were observed (Fig. 1).

Wax as support material

In the Test B the same substrate composition was used. Support structure was made from melted wax without any additional growth bucket.

In the process, layer by layer, thin wax walls were formed and then the space was filled with the substrate. During the 7 days a stable growth process inside the wax shell was observed. However, after removing the wax shell, the structure exposed was far more brittle than the result of test A. The reason for that was insufficient compression force provided by wax, as well as consecutive wax layers intersecting the substrate and not allowing it to grow a dense shell-like skin holding all the substrate together (Fig. 2).

Path 2: Inner scaffold of hemp strings acting as lost formwork

This prototype aimed at creating porous, branched samples. The hemp strings were boiled in water to sterilize and later soaked in the starch liquid to provide rigidity. Then it created the targeted form by tying strings together. Later the mycelium material substrate was manually applied on to the strings and pressed around the strings manually. The prototype was growing in the plastic box growth chamber, with small holes pierced on the lid. Before closing the walls of the box were sprayed with water. At the end of growth period the sample was dried in the oven at 80 °C (Fig. 3).

Path 3: Tubular stretch bandage acting as thick filament

The third approach was rethinking the relationship between the mycelium material and continuous tubular

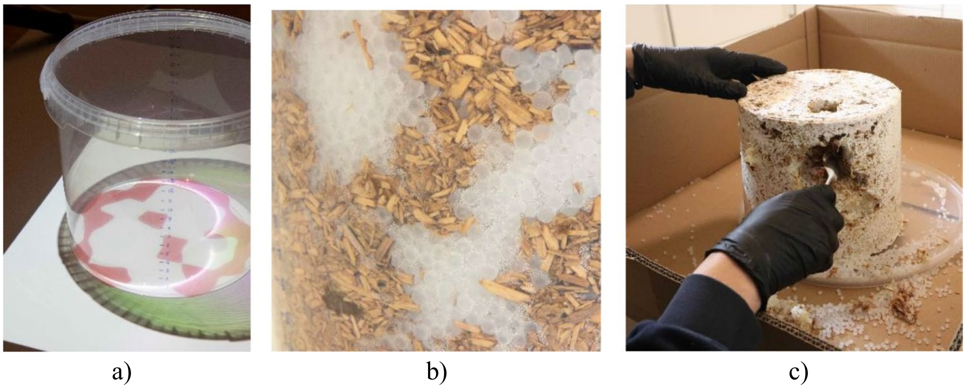
a) b) c)

Fig. 1 **a**) Bucket with the projection and marked deposition layers, **b**) zoom on substrate and the granulates support material, **c**) extracting support material; ©IBK2, Student: Daniel Pauli / University of Stuttgart


a) b)

Fig. 2 **a**) Test B sample after growth period, **b**) Test A and Test B after oven drying; ©IBK2, Student: Daniel Pauli / University of Stuttgart


a) b)

Fig. 3 **a**) hemp strings after soaking and bringing into form, **b**) sample after drying; ©IBK2, Student: Tian Mi / University of Stuttgart bandages. Stuffing of the tubes allows for creating continuous, bendable filament, where material is continuously pressed in the process of stuffing, which allows for good surface connection between the substrate particles. As inoculated substrate is fragmented, but is not liquid, which allows for usage of permeable, textile tubes in the process. Tubes out of cotton-viscose, nylon and polyamide-elastane nets were tested.

Cotton-viscose tubes

Cotton tubes were bought as the tubular bandages (Lohman-Rausher tg Schlauchverband) with 3 cm diameter size. Before use, tubes were sterilized in an autoclave. Attempts to stuff tubes with the use of a hand operated stainless-steel sausage-stuffing machine were unsuccessful. Inoculated substrate was blocking itself in the circular opening in the side of the cylinder where normally material is extruded. The friction of the substrate was too big and didn't work with the device optimized for the use with the viscous and more wet material. Therefore, tubes were stuffed with the use of the 1-m-long aluminum pipes. The bandages were first pulled on the pipe and then stuffed by moving substrate in the pipe with the use of a second pipe with a smaller diameter and closed ending. After stuffing, bandages were hung and braided (3 bandages simultaneously) or twined together (2 bandages) into the target form of branching columns. In the first-round filaments were protected from drying by wrapping plastic foil around hanging scaffolds. In the second attempt the foil was wrapped around the bandages and material was additionally sprayed with water to increase humidity (Fig. 4).

Nylon tubes

In this fabrication method nylon 4 cm in diameter tubes (sterilized by soaking in ethyl alcohol and drying) were stuffed with the mycelium material. After each 4–8 cm the tube was stretched around material stuffed by hand and tight to keep the substrate pressed and create the elements of variable length. Subsequently, the elements were put on top of each other with changing orientation, creating a column with a bulky appearance. The stability and the vertical form are provided by the means of the geometry of the stuffed elements. The parts of the filament were pressed manually together during the lying process. The prototype was grown in the plastic box, with one side protected with the foil and small holes pinched for ventilation. The inner sides of the box were sprayed with the water before closing. The piece was growing for 6 days after which the growing chamber was open and it was moved to the oven for drying in 80 °C. After drying the prototypes were subject to 70 kg of distributed load test. Only minor deformation was visible on the surface of the model, mainly due to its spherical shape and force concentration (Fig. 5).

Polyamide-elastane nets tubes

Stretch net tubes from polyamide-elastane were bought as the medical material for stabilizing bandage on members. Nobamed Schlauchverband Nobanetz were purchased in the size 0,5-Toe. They were sterilized by soaking them in the ethyl alcohol and later dried under the air flow from the ventilator directly before use. The chosen method of stuffing was using the tube of the 50 ml syringe on which the 2-m-long net tube was first pulled and compacted in the length of the syringe (10 cm). The mycelium material was put into the syringe tube and then extruded by gently pressing it with the fingers in the tube. The material was extruded with the nets step-by-step tensioning around the material and keeping it together.

In the first round the tubes were hung on the hooks and braided into a form. The growth chamber was built as the cage from PE-foil nailed to the wooden scaffold. The air filter of around 5 × 5 cm was placed on the side of the chamber to allow for the air exchange. Before closing the inner sides of the chamber were sprayed with water. The structure was growing for 6 days with the 90% humidity and constant temperature of 27 °C. After

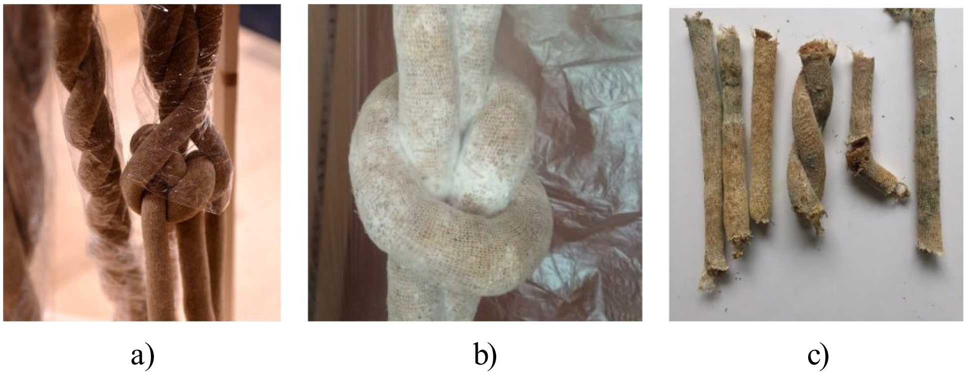

Fig. 4 **a**) bandages after hanging, **b**) initial growth after 4 days **c**) samples with green mold; ©IBK2 / University of Stuttgart

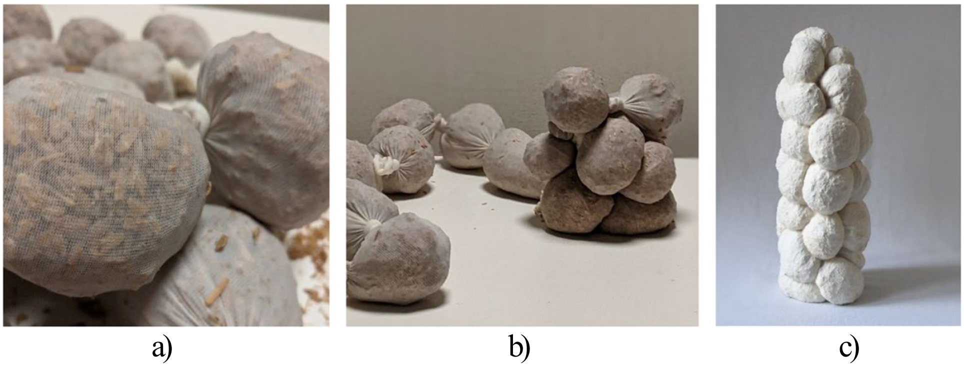

Fig. 5 **a**) tubes stuffed with mycelium, **b**) positioning of the elements **c**) samples after drying; ©IBK2, Student: Anastasia Malafey / University of Stuttgart

the end of growth period the structure was air dried. In the second round the tubes were stuffed with the mycelium material without the added flour and put in a circular, layer manner in the plastic box growth chamber. It was left growing for 6 days after which it was air dried (Fig. 6).

Conclusions and argument

The investigation paths can be perceived as an investigation into form-producing methodologies leveraged by the changing character of the material, which transforms from loose, wet and heavy into solid, light and hard within the biological

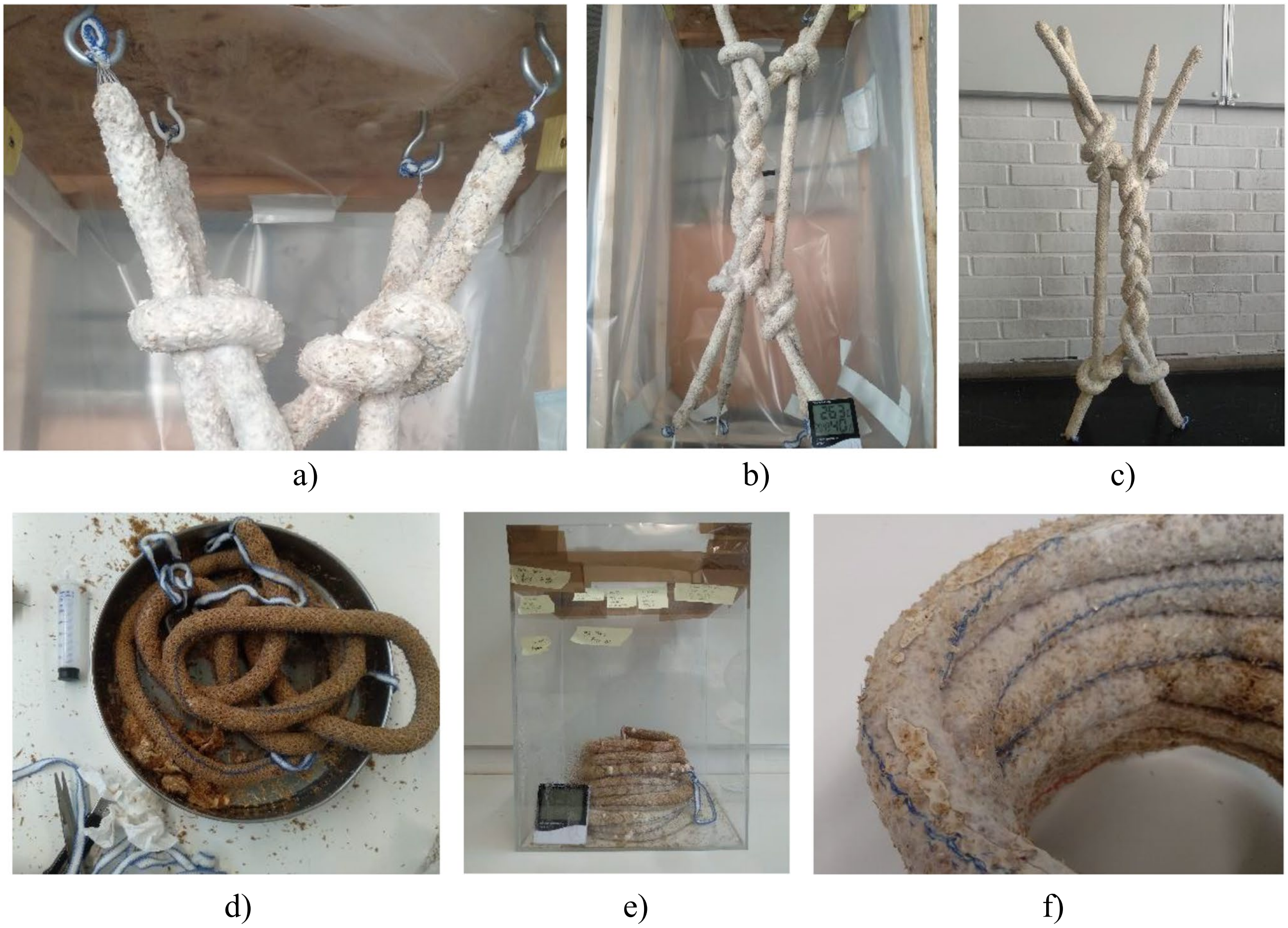

Fig. 6 **a**) hanging elements, **b**) growth chamber after opening **c**) samples after drying **d**) tubes stuffed with inoculated material **e**) plastic box growth chamber **f**) sample after drying ©IBK2 / University of Stuttgart

project of self-assembly by the fungal growth. All three fabrication methods are a cases of molding, which, thanks to the application of the multi-step fabrication process, proved to be feasible for the creation of biodegradable mycelium biocomposite structures. The methods are original and do not have precedents in previous publications. The spatial qualities they unfold are exciting and promising; however, their direct architectural application is unclear now. The scale of investigations can be perceived as the 'model making' of the architectural spaces, bearing the question of which factors would make upscaling possible. It refers to critical factors like.

- the maximal depths of the continuous material,
- the porosity of the proposed forms,
- the water transfer within the material during the growth phase
- the contamination risk during a prolonged period of building time.

Presented paths take the opportunity from MCB quality and related processes:

- Providing internal aeration as the form design driver.
- Embracing the emerging surface patterns as the main aesthetical quality of the resulting work. Standing the opposition to smooth and flat surfaces of the industrially produced materials.
- Take advantage of the elasticity of the material during the beginning of the cultivation, allowing for further form manipulations

Further integrated interdisciplinary studies and tests are needed to assess the application prospects.

Between the tree methods, when looking at their spatial appearance, the common aspect of porosity of forms can be observed. It refers to the openings in volumes and the uneven surfaces resulting from the protrusion of the substrate fibers from the perforated molds. These aspects, from the creative perspective can be perceived both as the treat, and as the natural language of the material which could be used creatively in the design process.

Two- phase printing

Compression of the substrate, and the friction between the gravel pieces was acting as the material regulatory aspect for the compression of first phase material. Interesting would be to investigate how consistent density can be achieved in the manual deposition process. With the hand deposition depending on the pressure applied the volume 'tightly packed' into the mould can vary significantly—even by up to 50% in case of wet hemp-straw substrate.

Inner scaffold of hemp string

The methode bears the strong handcrafting characteristic, as the initial construction of the 3d scaffolding as the bunches of stiffener strings is created directly in 3d in the manul process. Therefore the reproduction of the blue-print of the design is limited if not impossible.

Also the scaffold on which the inoculated past is applied is elastic, not rigide, therefore the application process further deforms the scaffold.

The path bears the promise of further investigation of the potential of stiftening the fibrous structures with the MCB paste (consisting of the fungi inoculated short fibers and additives) acts as the stiffening matrix for the long fibers. It can be considered as a speculation for the potential development of a winded long fibers construction systems as a totally bio-based solution. Mycelial network of hyphe can be perceived as bio base matrix in natural fibers composites. It is the readily available investigation direction, standing as the alternative to market available alternatives of (bio-)resins, which by now are the only available methode for stiftening long fibers.

Tubular stretch bandage acting as thick filament

Using tubular bandages implies a significantly higher risk of contamination with mold (especially with cotton bandages) due to the duration of the manual deposition compared to the other undertaken paths. Also, this path seems to have the highest automatization potential as it could be easily translated into the work of a big-scale 3d printer with custom nozzles, either robotic arm with a custom end effector. Upscaling the filament in a process which leaves a lot of room for the material viscosity, provides a friction between the layers due to the rough surface of the filament and allows for the cantilevering of paths due to the increased tension performance of the filament looks promising. The bio-welding characteristic of mycelium, which allows for connecting the gaps up to 2 cm [16] when grown in the suitable condition, when paired with the pre-assembled tubular filament, can open a new design space for the upscaling endeavors.

Outlook

The transition from loose to solid in the cultivation process makes MBC suitable for additive fabrication. Therefore, initial design-oriented experiments with mycelium composites developed around the recreation of archetypal forms of building elements, namely bricks and plates. They proved it as a suitable fabrication method for recreating known building forms with the new material. However, such production of elements bears two limitations. The first is the dimensions limited by the depth of air penetration needed during mycelium's growth. The second limitation is the dependency of the element shape on moulds. Each newly envisioned shape requires a new mould. Due to their easy sterilisation and easy handling in laboratory-like conditions, polypropylene molds are the most common in MBC's fabrication. Casting in moulds is a ubiquitous method in industrialized production and proved to be highly efficient in mass production. However, building practice nowadays craves for the new, more sustainable material practices, which could be embrace and adopted on the base of different factors then pure economical calculation. The growth of mycelium composites allows one to envision it as a suitable material for easy, waste-free production of custom, structurally optimized, organic 3d forms, which could gain adopters due to different formal expression then ubiquitous modern, international, industrialized form production expression.

All the presented methods show promising upscaling prospects. However, further studies of these fabrication methods should focus on their automation through robotic fabrication, resulting in increased precision of execution and repeatability of the results. Only then will testing the physical properties of the samples built with presented fabrication methods show reliable results. Success in this field could finally allow for an introduction to the mainstream architectural application of the biomaterial, allowing for casting and giving enormous freedom in creating 3d forms.

Conceptualization of the proposed structures with other natural materials such as softwood or fiberboards could not be realized through standard, exclusively additive processes and would require multiaxial CNC milling, generating significant material waste. Also, the field of natural fiber composites utilizing resin matrixes applying both short and long fibers cannot deliver similar formal results as it bears a different and distinctive aesthetic.

The presented design speculations with living material show that going beyond established fabrication protocols is possible and that additive fabrication can be further researched and developed beyond straightforward, understood casting.

However mostly, the presented experimentations are opening up the question if the advent of biological material and composites can contribute to the creation of the bio-technological construction process, which would allow for the high precision, grading and differentiation of form and internal structure of the building matter. Subsequently allowing for the more considered and efficient utilisation of the resources in the built substance.

The attempts to build with living material whose biological properties are still unknown and are the subject of fundamental research investigation may be considered unproductive and contradict the Technology Readiness Level (TRL) [32] of MBCs. However, in our view, the development of MBCs for architectural applications has to be inscribed into the circular feedback loop between the rigorous process of microbiological investigation of material and free design-driven experiments in construction in a macro scale. The macro-scale experiments can help target microbiological investigations, which inherently operate in the reality of an infinite amount of variables where all of them cannot be tested simultaneously with comparable care due to the time and research resource limits.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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