Digital biofabrication – sound architecture and mycelium

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Abstract

The search for sustainable and biodegradable materials has been growing to replace petroleum-derived materials, commonly used by industry. Therefore, FabLabs have been investing in products produced from digital biofabrication, which is based on the concept of circular economy. At the same time, the world is undergoing a constant change and reframing of living standards, in which people seek comfort, well-being and quality to live. In this sense, leisure, work and home environments need acoustic treatments in order to minimize the impact of noise perceived by users. The objective of this paper is to present the process of defining an open source design methodology for the production of mycelium-based composites, from biofabrication using by-products and agricultural waste, with low energy consumption, aiming acoustic applications. The entire product development process was carried out at the FabLab of the Exact Sciences Campus of the Centro Universitário Newton Paiva, in Belo Horizonte, Brazil. Finally, this article concludes on the possibilities of integrating biomimicry into design, computational technology and synthetic biology for the production of efficient and environmentally friendly materials at low cost as an alternative for the market.

Keywords

Biomaterials, Sustainability, Digital Biofabrication, Mycelium, Sound Architecture

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1 Introduction

In 2015, the Paris Agreement brought together 195 countries that committed, among other measures, to rethink production models on a global scale (UNFCCC). Since then, production value chains have been rethought by global leaders. The constitution of the Economic Forum for Circular Economy came with the ambitious goal of bringing together public and private organizations, scientific community and civil society to accelerate the transition through waste disposal and the sustainable use of natural resources (Mitchell, 2017).

A global change in the way we produce and consume implies a rapid evolution of production systems, and just like the revolution brought about by the personal computer and the Internet, digital manufacturing technologies have initiated a radical transformation in industry and consequently in global production and consumption in the last decade (Gershenfeld, 2012). And Fab Labs have become important players in this transition.

The term Fab Lab is short for Fabrication Laboratory. Conceived in 2001 by Prof. Neil Gershenfeld, director of the Center for Bits and Atoms at M.I.T. to teach the course ˜How to Make Almost Anything', Fab Labs are open, interdisciplinary laboratories that bring together digital fabrication technologies. The international Fab Lab network currently consists of more than 1,900 Fab Labs in more than 100 countries. - Fab Foundation (Fabfoundation.org).

The worldwide network of Fab Labs has given rise to initiatives such as Fab City Global, which incorporates the parameters of the Circular Economy into digital manufacturing, with a focus on urban development. A manifesto signed in 2014 by the Instituto de Arquitectura Avanzata de Cataluña (IAAC) and the Fab Foundation (Center for Bits and Atoms - M.I.T) would invite cities to totally transform the way they produce and consume, using digital manufacturing technologies and the international network of Fab Labs for this transformation (Diez, 2017).

It is increasingly recognized by all that the linear process of consumption and production prevalent since the Industrial Revolution contributes to global warming, and the Circular Economy has been an increasingly frequent theme in the World Economic Forum (Macarthur, 2013).

The experience within Fab Lab Newton - a digital fabrication lab accredited by M.I.T - brought to light a problem common to all digital fabrication labs: the use of highly polluting raw materials and poor waste management. In 2018, Fab Lab Newton became a partner with the City of Belo Horizonte in the Fab City Belo Horizonte project (Horizonte, 2019). The challenge of Fab City Belo Horizonte is to make the city fully sustainable, self-sufficient, locally productive and globally connected, by building a network of partners that share knowledge to solve local challenges, with global solutions (Diez, 2018). Since then, the principles of Fab City have been applied in the daily life of the lab, especially regarding the disposal of materials.

Digital manufacturing, considered one of the main factors for the technological democratization promoted by the so-called third industrial revolution, will only survive in a world guided by sustainable development if the inputs currently used are replaced by those that follow circular production chains (Troxler, 2014). In this scenario, an increase in the search for sustainable materials and production cycles has been noted in the global Fab Labs network, and open projects for the production of Biomaterials and independent research groups such as the Biofab Forum - BioFab Forum (https://biofabforum.org/c/biomaterials) have started to spread, making innovation through Digital Biofabrication increasingly accessible (Pistafidou et al., 2020).

These digital platforms are open-source databases that enable the sharing of practices and inspirations, and transdisciplinary collaborations with the goal of finding sustainable and affordable solutions to wasted resources. This nurtures a decentralized manufacturing approach, as opposed to patents and intellectual property (IP) control (Troxler & Wolf, 2010). In this context, personal manufacturing can become an alternative to mass consumption for more citizens as they gain access to digital manufacturing opportunities (Kohtala, 2017).

As pointed out by Ratto (2011), open design provides a more critical look at current practices, whether in institutions, companies or consumers, in a society mediated by technology and information. The FabLab is a perfect stage for this theme known as "Critical Making" (Ratto, 2011), since these are community workshops where people use equipment to create, in a social and collaborative process (Kohtala, 2016). The sharing of files and production and design instructions has become a necessary tool for projects and initiatives that seek to convey a critical dialogue about how to make, produce and manufacture things that now dominate the lives of city dwellers (Troxler, 2019).

Although sustainability is a topic frequently addressed in the annual meetings of the international Fab Labs network, initiatives with real results are still scarce. Notable in this regard are Precious Plastic (Hakken, 2013), a line of open source equipment for recycling plastics, including filaments for 3D printing; and Fabricatable Machines (Fossdal et al., 2020), an open source tutorial for building low-cost digital manufacturing machines.

In 2020, the covid-19 pandemic brought scenarios hitherto outside all the standards outlined by the scientific community. This unprecedented context awakens the urgency to make the practices proposed by the Circular Economy and the democratization of digital manufacturing technologies faster and more accessible. These factors, coupled with the mapping of local resources for sustainable production of bioproducts, constitute the appropriate ecosystem for us to ask the question: instead of transforming, producing, and discarding, can't we grow products?

2 Fungi and Mycelium

Fungi are a natural, renewable source of structural polymers. Fungal cell walls are present in hyphae, which together form a fibrous and very strong network called mycelium. Mycelium has been identified as the largest living organism on Earth (unique individuals of the genus Armillaria have been identified colonizing more than 100 ha of soil) (Ferguson, 2003; Smith, 1992). Because of their chemical composition, they can be compared to wood and cork for mechanical strength properties (Appels et al., 2018). In this case, this net filled with a substrate acquires lower densities and higher resistances than pure mycelium (Jones et al., 2020), which propitiates us the reuse of agricultural waste, making the production process sustainable, of low energy consumption and ecologically beneficial with carbonic gas absorption during its growth and storage in the soil (Schwartzberg, 2019), being a realistic alternative in substitution to petroleum-based materials (Haneef et al., 2017). Depending on the feeding substrate, the final fibrous structures show different relative concentrations in polysaccharides, lipids, proteins and chitin, which are reflected as changes in the morphology of the composite and its mechanical properties. The mycelium is mainly composed of natural polymers such as chitin, cellulose, proteins, etc., so it is a natural polymeric fibrous composite material.(Haneef et al., 2017).

The process of production of mycelium-based biocomposites starts from the selection of the substrates to be adopted and the species. Several works on the production of these materials (Apples et al., 2019; Attias et al., 2017; Haneef et al., 2017; Ghazvinian et al., 2019; Holt et al., 2012) point to the use of wood-rotting fungi, the basidiomycetes that cause white rot, as they degrade primary wood components and lignin (Alonso et al., 2007), without causing considerable losses of cellulose and hemicellulose (Luz et al., 2012; Schimidt et al., 2003). Especially species of the genus *Pleurotus* are relatively easy to grow and can grow on a large amount of moistened and sterilized or pasteurized substrates (Elliot, 1997) such as cereal straws, dried grass, foliage (Madan et al., 1987; Schimidt et al., 2003), sawdust (Fasidi, 1996), corn production waste, seed husks, coffee waste (Nunes et al., 2017; da Silva et al., 2010; da Silva et al., 2012), sugarcane bagasse (Moradali et al., 2007), paper, cardboard and by-products of the paper industry, among many others (Chang and Miles, 1989; Fan and Ding, 1990; Yang, 1986). It was also observed that the species *Pleurotus Ostreatus* obtained a good development adopting oxo-biodegradable plastic as substrate, contributing to its degradation (da Luz et al., 2013), besides other pollutant materials and substances such as oil, among other petroleum derivatives (Ahmadi, 2016).

From the variety of materials and their different chemical compositions, it is possible to predict the development of fungal species and applications of the resulting mycelium-based compost. However, the use of these cheap and relatively low quality materials as substrates, having little cost and high environmental sustainability, can compromise the quality of the compost and influence its properties

(Jones et al., 2020), although it does not harm the development of the fungus that can nourish itself from this nutritionally poor waste due to its enzymatic complex (Bernardi et al., 2021).

Being mycological biopolymers, mycelia provide a natural, compostable alternative. They reduce the cumulative use of fossil fuels, eliminate the need for conventional and energy-intensive chemical extraction, refinement and synthesis. Among these advantages are high reproducibility, low toxicity and a sustainable life cycle.

It is possible to develop fully sustainable mycelium-based bioproducts for use as input in digital manufacturing technologies from agricultural surplus, creating a circular production chain that benefits fair trade and promotes local development (Bhardwaj, 2020).

3 Sound Architecture

The world is going through a constant change and resignification of life standards, in which people seek comfort, well-being and quality of life. In this sense, the environments of leisure, work and residences need acoustic treatments in order to minimize the impact of noise perceived by users.

According to the World Health Organization (WHO), noise pollution, along with air pollution from gaseous emissions and water pollution are the three ecological priorities (Berglund, B., et al). This reflects significantly on the largest proportion of the population, as more than 55% of people in the world live in urban areas, major generators of impact on human health, and the proportion is likely to increase to 68% by 2050, according to the WHO (World Health Organization). Excessive noise seriously harms human health and interferes with people's daily activities. Far beyond the nuisance and hearing loss, the effects may be cardiovascular and psychophysiological in the short and long term, such as increased production of corticoids, adrenaline and noradrenaline that lead to changes such as tachycardia, peripheral vasoconstriction and elevation of blood pressure, causing permanent disorders, or stress. These symptoms can extend to nausea, headache, irritability, emotional instability, reduced libido, anxiety, nervousness, loss of appetite, drowsiness, insomnia, hypertension, visual disturbances, as well as fatigue and reduced productivity (Gomes et al., 1989; WHO, 1999).

In this sense it is necessary to contribute to the improvement of these conditions in order to limit and control the exposure to environmental noise, seeking better planning, efficient building systems and materials with great acoustic performance. The products available in the market today are based on synthetic fibers and petroleum derivatives, whose production is expensive and has a great impact on the environment. This requires high consumption of resources, generates high levels of carbon emissions and problems in disposal, since these materials take thousands of years to degrade.

Mycelium-based foams have shown, through research, to be an alternative as a substitute for hydrocarbon-based products, such as polyurethane (PU) foams. This, in addition to having great acoustic performance, is also an excellent thermal insulator.

Currently there are a few pioneering companies in the world that produce the composites commercially, such as Ecovative Design, Krown Design, and MOGU, which produce, in addition to packaging, insulating panels and acoustic tiles (Elsacker et al., 2020). The acoustic panels developed by MOGU are sold with a Noise Reduction Coefficient (NRC) of 0.4-0.53, a replacement alternative to commercial acoustic models (Pelletier et al., 2017 apud Elsacker et al., 2020). In addition, mycelium-based acoustic products also work well as thermal insulators (0.05 W/mK), and are a possible replacement for PU (0.006-0.18 W/mK) and expanded polystyrene EPS (0.03-0.04 W/mK), despite the latter's poor acoustic performance. Engineering firm Arup is developing sound-absorbing surfaces for interior fittings in collaboration with start-up company MOGU (Bio-Composite Systems for Interior Fit-Out - Arup, 2019 apud Elsacker et al., 2020).

Recent research demonstrates the efficiency of applying mycelium for acoustic coatings and insulation. Pelletier et al. (2013) examined the acoustic absorption applications of mycelium grown on agricultural by-product substrates and tested as this new composite is limited in density control, with the main control being the selection of constituent parts. The testing of the material for use in acoustics used an impedance tube and measured the stationary wave ratios according to the ISO 10534-1 standard. The results of the study show that the mycelium-based boards are a promising bio-based composite alternative to the standard traditional foam insulation board. The results suggest optimal performance at the automotive road noise frequency of 1000 Hz.

Yang et al. (2017) analyzed the mycelium-based acoustic foam produced by mixing different substrates, including sawdust, millet grain, wheat bran, and calcium sulfate. The research demonstrated that the densely packed samples have results that met or exceeded the characteristics of conventional polymeric foams, except dry density. The results demonstrate that this mycerium-based acoustic foam offers great potential for application as an alternative insulation material for building construction and infrastructure, particularly in cold regions, or as a lightweight fill material for geoengineering applications (Yang et al., 2017).

Pelletier et al. (2019) examined the acoustic absorption properties of mycelium-based natural biopolymer in the range of 350 Hz to 4 kHz. The results of the study indicate that this new class of foam represents a sustainable alternative as it is an all-natural bio-based fiber for acoustic shielding compared to traditional acoustic absorbers.

The objective of this paper is to present the process of defining an open source design methodology, at the current stage of research, for the production of mycelium-based composites for acoustic applications. This encompasses from the conception of these products, production of the molds, choice of substrates obtained from agricultural waste and local disposal, and species suitable for this purpose. From the analysis of the production methodologies adopted in several studies already conducted, it will be possible to propose a suitable one for this type of product.

4 Method

Based on the concept of Critical Making from interdisciplinary practices, the FabLab brought together other laboratories in collaboration with this project, such as the Chemistry, Structural Engineering and Materials, and Microbiology labs.

In order to implement the circular production chain through the use of local waste - one of the values advocated by the Global Fab City Network (Diez, 2017) - agricultural waste was collected from a subsistence crop in the city of Formiga, in the southeastern part of the state of Minas Gerais, Brazil, near Belo Horizonte.

Substrates with performance already tested and proven in the scientific literature were selected, such as bean straw, coffee husk, corn straw, sugarcane bagasse, and brachiaria grass.

Brazilian wood waste such as Hymenolobium and Tectona grandis and MDF waste by CNC, both from the Fab Lab Newton, also composed the substrate tests in comparison to those already studied by other authors (cf. Figure 1).

a. b. c.

Figure 1: Types of natural fibers adopted in the research: a. corn straw (CS); b. bean straw (BS); c. coffe husk (CH); d. sugar cane snuff + brachiaria grass + hardwood sawdust (CS+BG+HS); e. FabLab hardwood sawdust (HS-FB); f. FabLab mdf powder (MDF-FB). *Source: image from the author*

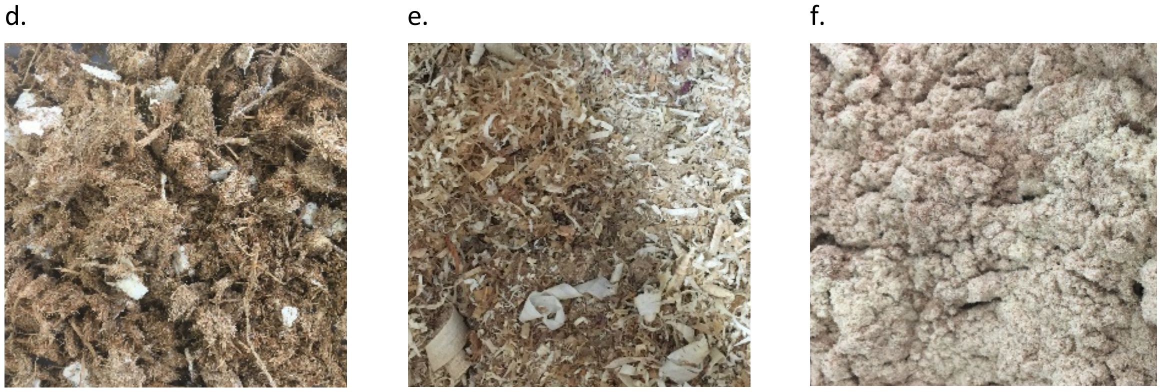

Figure 1: (continued)

The mushroom species adopted for this study were provided by the company Cogu das Minas, a mushroom producer based in Belo Horizonte, and they were*:* *Pleurotus ostreatus* (shimeji), *Pleurotus ostreatus shimofuri* (shimofuri), *Pleurotus citrinopileatus* (citrus or yellow shimeji) and *Pleurotus djamor* (salmon shimeji). These strains are widely adopted in similar research because, as already mentioned, they are easy to obtain, grow on various types of substrates, and generate materials with good characteristics (cf. Figure 2).

Figure 2: Types of fungal species adopted: a. Pleurotus ostreatus (shimeji); b. Pleurotus ostreatus shimofuri (shimofuri); c. Pleurotus citrinopileatus (citrus or yellow shimeji); d. Pleurotus djamor (salmon shimeji). *Source: https://www.fungicultura.com.br/especies/*

4.1 Bio-inspired design

As a bioproduct, the creative process had as main criterion to represent the close relationship with nature. The scope was finding forms from nature whose geometry allowed modularity and aesthetically represented the mycelium. Thus, the lessons of Biomimicry connects technology to nature to find design inspiration in technological processes. The creative process was then inspired by Biomimicry DesignLens, an open source design toolkit (Biomimicry 3.8, 2015) based on Life's Principles by Janine Benyus (2002). (cf.Figure).

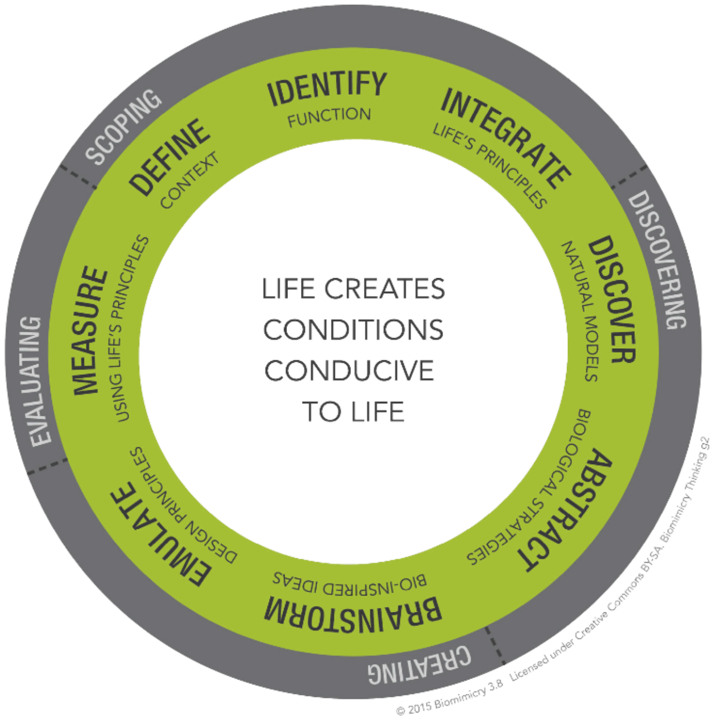

Figure 3: Biomimicry Thinking Toolkit by Biomimicry 3.8. Licensed under CC-BY-SA. *Source: http://biomimicry.net/about/biomimicry/biomimicry-designlens/lifes-principles/*

Another criterion was to find shapes that meet the parameters of the production technologies of the molds in the Fab Lab Newton. 3D printing was chosen for the production of the mold designed in .stl format, using 2.75 mm filaments of Polylactic Acid (PLA) and vacuum thermoforming for the reproduction of the mold as a formwork in Polyethylene Terephthalate Glycol (PETG), both biodegradable materials. In this case, the appropriate width for seamless production is 22 cm.

A modular geometry that is easily reproduced in 3D is found in the hive shape. For the heat deformation process generated in thermoforming, simple polygons are formats that do not suffer aesthetic loss in the process, generating easily reproducible moulds (cf.Figure).

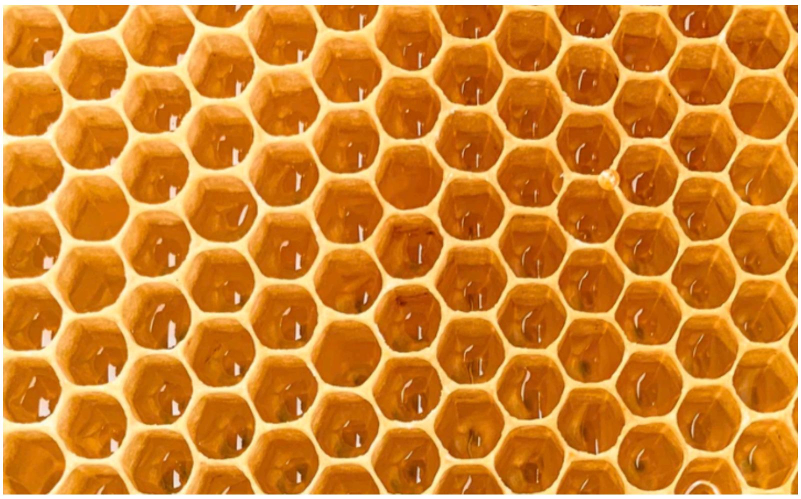

Figure 4: Honeycomb as biomorphic inspiration. *Source: Photo by Jonas Hensel on Unsplash (https://unsplash.com/@jns_hnsl?utm_source=unsplash&utm_medium=referral&utm_content=creditCopyText)*

For the surface, a mycelium network generates a pattern of triangles inspired by the mycelium network found in trees, in addition to creating a larger sound absorption surface (cf. Figure and Figure).

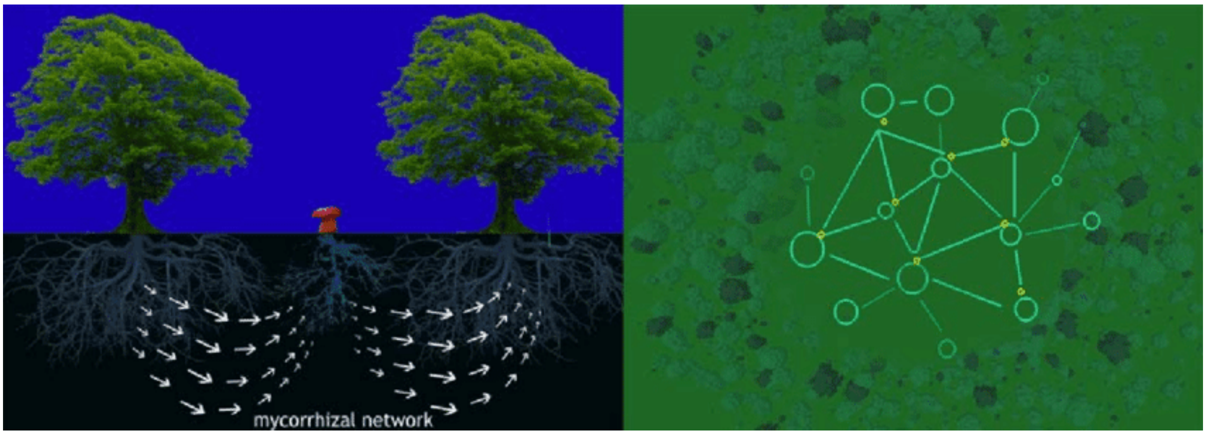

Figure 5: Mycorrhizal pattern network for biomorphic inspiration. *Source: Leudar, Augustine. (2016). Surrounded : A Series of Sound Installations That Combine Plant Electrophysiology and 3D Sonic Art. Leonardo. 51. 10.1162/LEON_a_01338.*

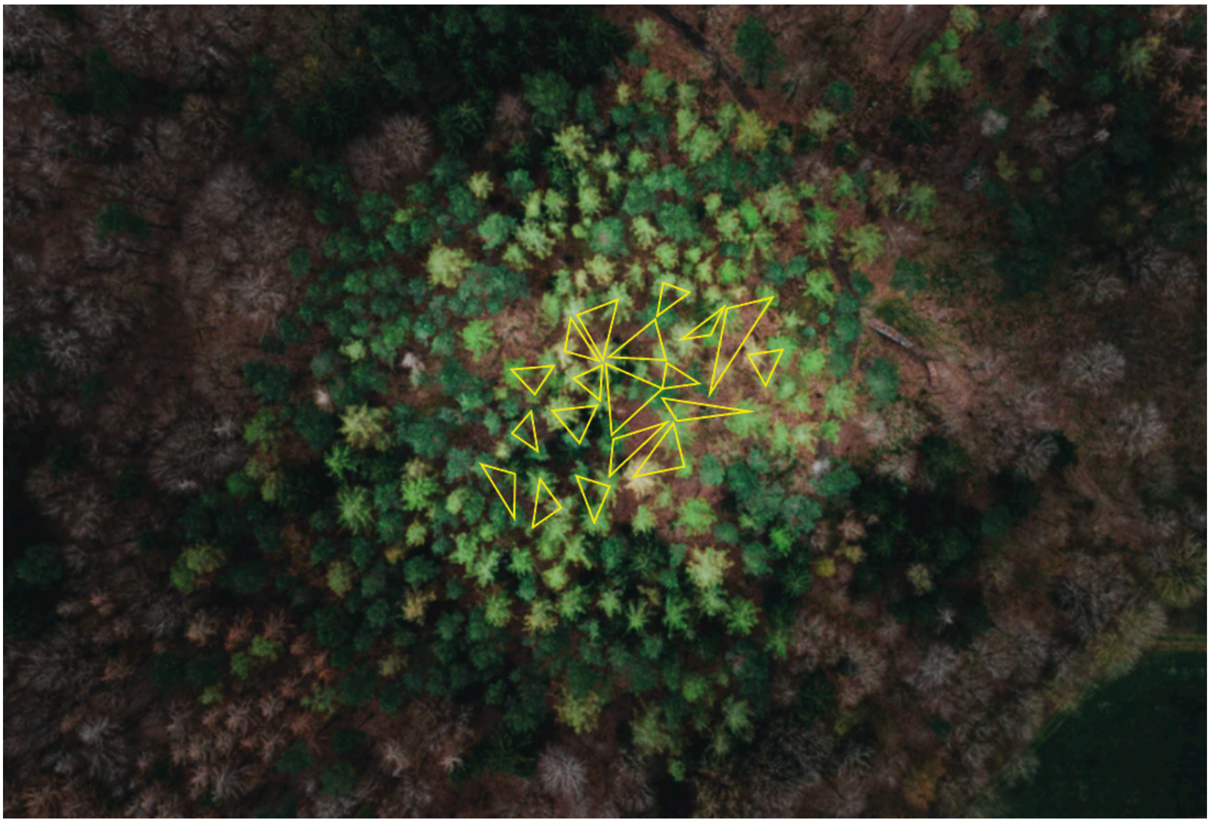

Figure 6: Mycorrhizal pattern network represented by triangles. *Source: Photo by Manuel Keller on Unsplash / graphic intervention by the author (https://unsplash.com/@emkaay?utm_source=unsplash&utm_medium=referral&utm_content=creditCopyText)*

The combination of these two aesthetic lines, allied to the production parameters of the 3D printer and the vacuum forming of the Fab Lab Newton, gave the result of the mould with a diameter of 22 cm and a width of 3 cm (cf.Figure and Figure).

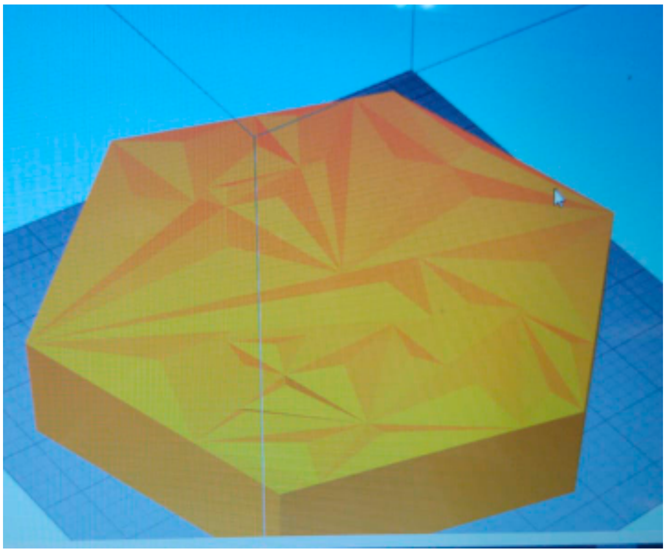

Figure 7: 3D modelling for vacuum forming mold. *Source: image from the author*

Figure 8: 3D printed mold for vacuumforming and the mold of PETG. *Source: image from the author*

4.2 Production of the mycelium composites

The technique for producing the composite materials consists, as mentioned initially, in the choice of the species and substrates to be colonized. In general, this follows a protocol that was compiled by Elsacker et. al (2020) from the review of open source manuals and articles, presented below and also illustrated in Figure, which demonstrates the entire production chain based on the concept of circular economy:

1. First, the mycelium is grown on nutrient substrates such as agar, grain or liquid solutions;
2. The substrate is autoclaved or pasteurized to eliminate any type of microorganism that could contaminate the growth of the healthy mycelium;
3. A small proportion of the already-grown mycelium is inoculated into the substrate, which is either pre-wetted (before autoclaving) or with a subsequent addition of sterile water. In order to enhance its development, a sterile nutrient solution can be added;
4. The inoculated substrate is placed in a sterile mold with the defined shape, and sealed with permeable film for air exchange;
5. The mycelium grows on the substrate in a controlled environment and under appropriate conditions. It can remain only in the mold, or at the end of the process, outside the mold to solidify its external surface;
6. The already grown material is treated at a determined temperature and time in order to stop its growth and dehydrate it;
7. A coating or post-processing may be applied to the material to improve its properties.

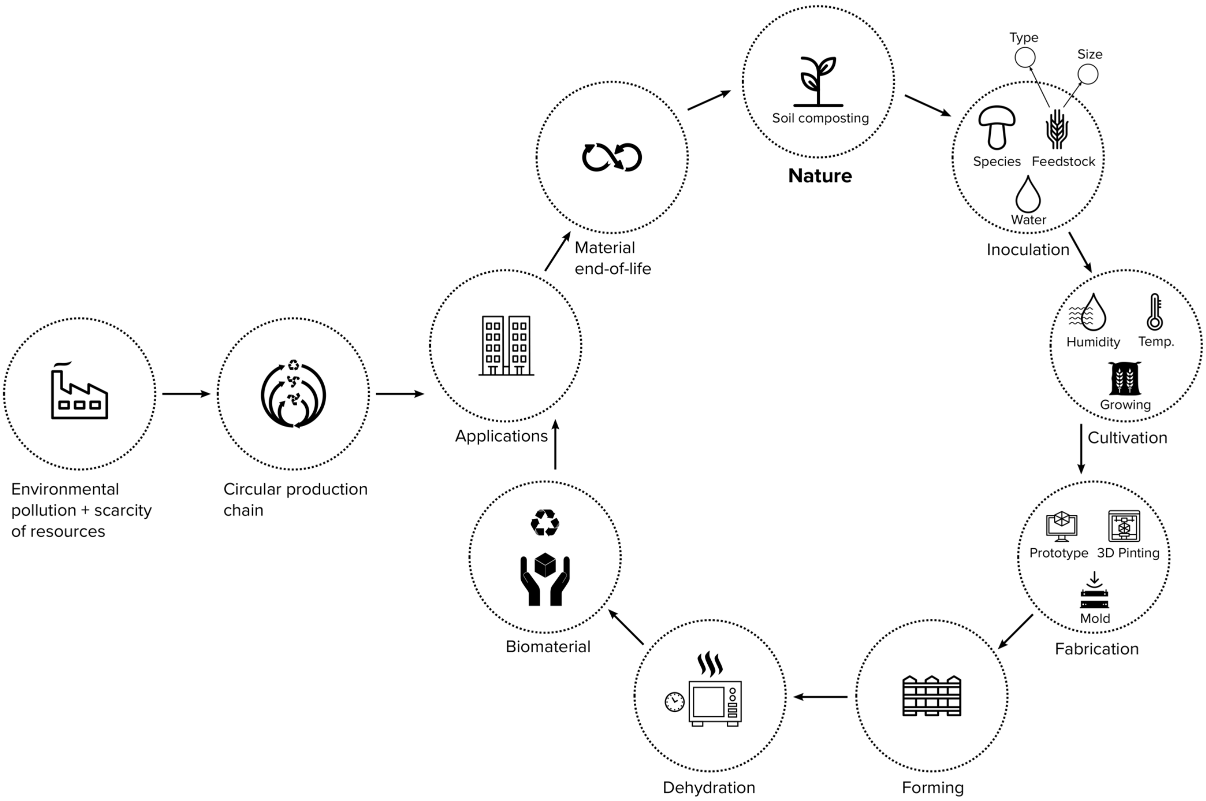

Figure 9: Process flow chart showing the applied fabrication method of mycelium-based composites. *Source: image from the author*

Steps 1 to 5 described above have already been completed in the research, and the biocomposites are in the process of growth in the molds until the substrate is completely colonized, is stopped its growth and dehydrated. Next, measurements and tests will be made to characterize them (cf. Figure) to verify their properties of sound and thermal absorption, density, mechanical strength and water absorption.

The various methodologies studied are being analyzed in order to propose the one that best suits the type of material proposed: an acoustic material.

Figure 10: Stages of the composites manufacturing process up to the moment of research: a. cultivation on nutritious substrate; b. spawn production; c. spawn colonized with mycelium; d. incubation of inoculated substrates with colonized spawn; e. start of mycelium growth on the substrate; f. pre-colonized substrate; g. transfer of the colonized substrate to the molds; h. intermediate stage of the colonization process in the forms, before dehydration. *Source: image from the author*

5 Conclusion

Mycelium is an inert, non-toxic, safe material and has become a viable alternative for obtaining an ecologically correct biocomposite material. In this sense, the use of mycelium for the production of materials for application in civil construction and acoustic material works as a conciliator of an expressive number of dimensions of sustainability. They reduce the cumulative use of fossil fuels, eliminate the need for conventional and energy-intensive chemical extraction, refinement and synthesis. Among these advantages are high reproducibility, low toxicity and a sustainable life cycle.

Currently the of mycelium-based material production is under the domain of industrial intellectual property of a few global companies and the biofabrication, through open source, is essential for sustainable production and promotion of communication and dissemination of information between the global scientific and engineering community.

This article concludes on the possibilities of integrating biomimicry into design, computational technology and synthetic biology for the production of efficient and environmentally friendly materials at low cost as an alternative for the market. The research is under development to create the process for defining the methodology for the biomanufacturing of mycelium-based material.

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