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Mycelium as a building material: current status and development perspective

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Abstract

Bio-based materials as the alternatives to the current energy-intensive building materials represent a new trend in the construction industry, to replace concrete or insulation sections. In this context, mycelium is recently introduced as the base material of novel net-zero-energy insulation composites, which reduce embodied and operational energy of buildings. This review aims to present and discuss the current development status of mycelium composites and to envision the prospective roadmap of its evolution in the building industry. Outcomes of this study indicate that mycelium's environmental footprints and embodied energy is significantly lower than traditional building materials and even some of its bio-based peers. Furthermore, due to its great insulation capacity, it offers a reliable capacity to be the alternative for traditional carbon emissive insulation materials, especially in severe climates, in which case insulation is indispensable. Mycelium's hygric capacity is reported higher than other insulation materials in water absorption. In addition to the beneficial subsequent moisture buffering, there are also some challenges in shrinkage and durability, which are reviewed. There are numerous processing and fabrication methods for composites, each of which could affect the resulting physical properties that are discussed throughout different studies. Cutting-edge projects on the usage of growing organism in building materials are cited as the last part of this review.

Keywords: bio-based materials, Mycelium, LCA, biogenic carbon, thermal conductivity, moisture buffer, porosity, water permeability

1. Introduction

Improving energy efficiency and reducing greenhouse gas emissions is nowadays becoming the key issue in all the sectors. In particular, the construction sector is one of the most energy-consuming industries (Moussa et al., 2018) and therefore, one of the biggest contributors to GHG emissions (Khasreen, Banfill, & Menzies, 2009). Today, there is a strive to meet ever more restrictive energy efficiency criteria, which is essential for the environment and global sustainability (Jansson, Schade, & Olofsson, 2013; Pan et al., 2015). Building sector contributes significantly to mankind's environmental footprint (Takano, Hughes, & Winter, 2014). Buildings are responsible for 40% of energy consumption and 36% of carbon emissions in the EU (Jones & Brischke, 2017). In Canada, commercial and institutional buildings account for 18% of energy demand, while the residential sector consumes as much as 33% of the national usage (*Energy Use in Buildings*, 2017).

One of the most important characteristics of a sustainable building is its energy efficiency; not only within its operation period, but also in each of the constituting element's life cycle phase. In retrospect, in implementing sustainability standards, the emphasis had been placed on the energy conservation within the building, whereas analyzing the entire life cycle of buildings, gives a broader vision of their total energy consumption and GHG emissions. Embodied energy, one of the neglected parts of buildings' emission, roughly accounts for 10-30% of a building's carbon emission (Beccali, Cellura, Fontana, Longo, & Mistretta, 2013; Cuéllar-Franca & Azapagic, 2012; Lawrence, 2015). Thus, it requires an exhaustive approach when it comes to study of the life cycle of materials and their embodied energy as well as their corresponding associated GHG emissions.

Currently, there is a growing shift in construction practices, towards bio-based low embodied energy and locally available building materials. Compared to the common or standard building materials (concrete, steel, and plastics), these substances have a range of beneficial properties such as low toxicity, durability, low level of GHG and other pollutants emissions, high recycling potential and minimal processing requirements (Joseph & Tretsiakova-McNally, 2010). In other words, moving from zero energy buildings (ZEB) to life-cycle ZEBs (LCZEB) could be the key approach to address sustainability issues (Dutil, Rouse, & Quesada, 2011). For this reason, correct selection of building materials can be performed by tracking them throughout their life time, and by choosing products with the minimal environmental impacts (Joseph & Tretsiakova-McNally, 2010).

Some of the industrial types of bio-based material like lime hemp concrete (LHC or hempcrete) or flax lime concrete (FLC) are currently being used in North America and Europe in a limited scope. However, mycelium bio-composites are the emergent type of crop-based material. These building blocks utilize mycelium as a natural binder as opposed to the traditional binders of bio-based materials such as lime. Incorporation of this material as an insulating building element not only highlights its usage as a natural binder of the crop-based substrates, but also it is currently being recognized as a fibrous reinforcing element of building blocks, effective in substantial change of the overall thermo-physical characteristics of building elements. The specific interest in this material is rooted in its three dimensional structure grown on the base substrate which is usually made of residues of other agricultural and forestry materials (Cerimi, Akkaya, Pohl, Schmidt, & Neubauer, 2019; Stelzer et al., 2021).

Various contribution potential of mycelium in the real-scale buildings could be in a wide range of buildings: from vernacular houses (simple low-impact buildings) to multi-storey buildings.

Research approaches that pertain to bio-based materials in the literature involve four categories of environmental, thermo-hygro-mechanical characteristics, social aspects and economic feasibility, and affordability (Gorse, Thomas, Glew, & Shenton, 2016). This study mostly focuses on the first and second category. Environmental issues involve studies on energy and water consumption, water conservation, material use, durability, waste, land use, transportation and GHG emissions, whereas the second category involves more standard engineering issues. Finally, characteristics of mycelium that enable new forms of reconciliation between art and engineering, discussed in a part of this study as well.

2. Mycelium-based composites' production practices

2.1. Proof of concepts

In fungi-based building bricks, cultivation of mycelium onto the substrate is conducted inside laboratory. This is done by cultivation of multicellular fungi which forms into dense mycelia while growing on the base substrate (Stelzer et al., 2021). Although there are diverse production practices found in the literature, the general practice includes the stages illustrated in Figure 1. As can be seen, sterilization, inoculation and incubation are the fundamental parts in growing mycelium on the substrate material. Various fabrication procedures are customized based on the need for achieving a specific thermo-physical characteristic. In order to layout the difference in emissions of this stage between mycelium composites and other bio-based materials, there is a need to detail other more advanced method of lab-scale productions of mycelium bio-composites.

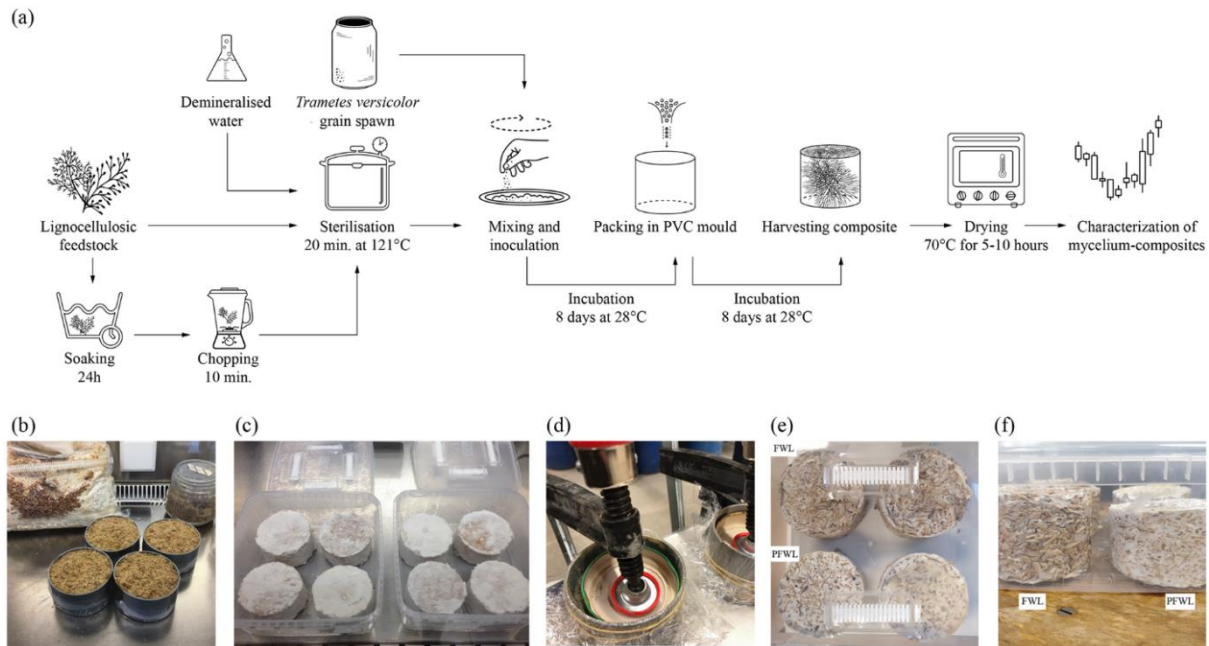


Figure 1. Fabrication process of mycelium bio-composites (Elsacker, Vandeloek, Brancart, Peeters, & De Laet, 2019)

Stelzer et al. (2021) introduced a three-stage procedure for cultivation of the mycelium and substrate. The essence of their idea is first to inoculate the fungus using agar into a pre-culture complete medium. Then, using a sterilized initial substrate to conduct a secondary inoculation (rye

is used in this research), and finally using that culture to incubate the main substrate, which is hemp shiv in this case. This way, the growth and distribution of fungi among substrate is claimed to be more efficient (Meyer et al., 2020; Stelzer et al., 2021). The LCA method suggested in this study is described in the manufacturing section of the paper.

Appels et al. (2019) described the importance of three elements including substrate, fungal specie and processing technique in the final hygrothermal, mechanical and visual characteristic of mycelium. Out of the tested substrates, sawdust showed a higher density than cotton fibers and straw. Pressing is claimed to increase the tensile strength and elasticity modulus of mycelium materials and hot pressing is mentioned to be more effective in doing so. There is no observed dependence between water absorption and any of the three analyzed elements. In contrast, they noted the influence of heat pressing to change the structure of material from foam-like performance to cork and wood-like performance, which is demonstrated in Figure 2; in terms of stress-strain representation of these two behaviors. The suggestion for further fabrication practices in this study is to enhance colonization in central parts of the composite, by for instance injecting air and oxidizing the central parts.

Other study on the fabrication parameters is conducted by Attias, Danai, Tarazi, Pereman, and Grobman (2019). Water absorption capacity of the three developed bio-composites made out of three fungal species grown on vine and apple as the substrates. These three bio-composites with different fabrication parameters are compared to each other in Figure 3. It clearly shows that low density samples absorb more water. These results also indicate that the two Expanded Polystyrenes (EPS) types tested, weigh about ten times less than the mycelium-based composites.

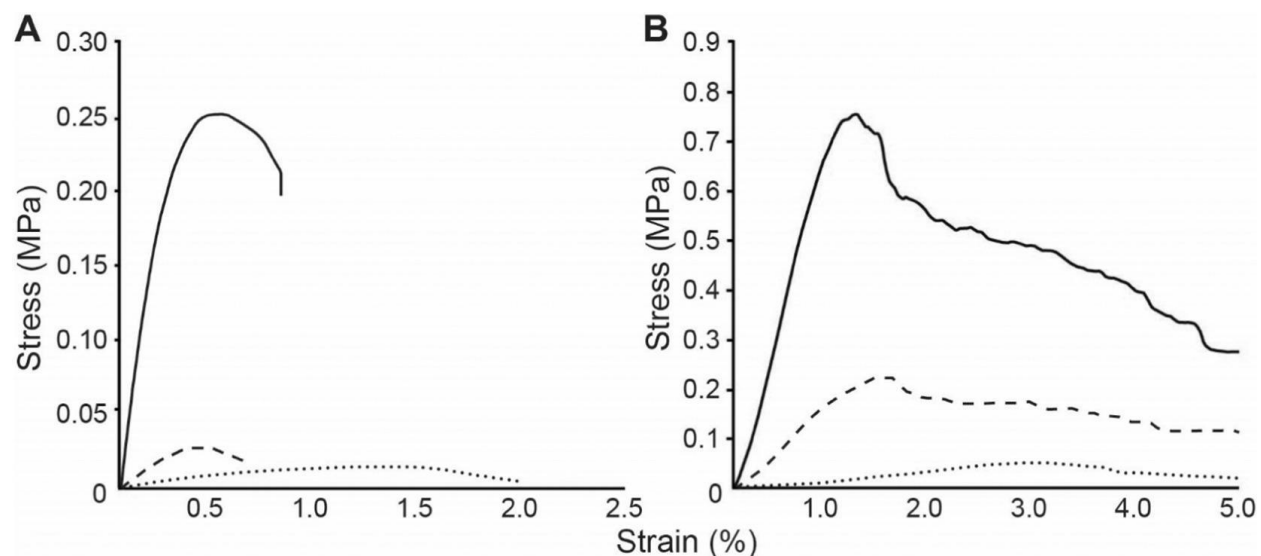


Figure 2. Tensile (A) and bending (B) tests of *P. ostreatus* grown on rapeseed straw without pressing (dotted line), and cold (striped line) or hot (solid line) pressing (Appels et al., 2019)

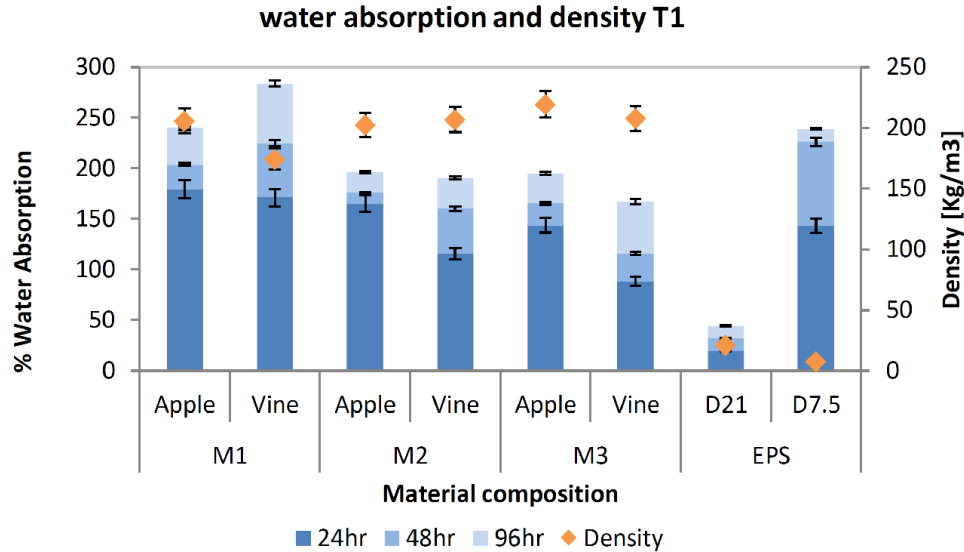


Figure 3. Comparative analysis to evaluate the effect of material composition and incubation method on density and water absorbance performance (Attias et al., 2019).

Mycelium is also identified as a complementary material in cutting-edge bio-composite architectural structures. Scott et al. (2022) fabricated a series of prototypes using the integration of mycelium and bacterial cellulose on knitted wool-based scaffolds. Their methodology “combines biological experimentation with parametric modelling and knit programming”. Knitted fabric acts as scaffold and mold to guide the bacterial and fungal growth to achieve complex curvaceous forms. Using the adjustability and modification of fabric parameters, during design and fabrication, growth of the organism can be adjusted. Another goal of this research is to introduce program knitting and its applications as shaping agents for both in-situ mycelium growth and secondary bacterial cellulose sheets.

The challenges in developing the prototype is reported to be the inhomogeneous distribution of substrate and therefore disrupted mycelium growth. A paste-like agglomerate is suggested as replacement for the chopped substrate to make the material more homogeneous. Fabrication process is illustrated in Figure 4. In order to integrate mycelium and bacterial cellulose structures, either two organisms are grown in one place, or they are grown separately and bacterial cellulose is placed on top of the mycelial structure, and then dried together. Another initiative of this study is to incorporate digital knitting to manipulate the design and parameters of knitting. Designed structures in this approach are reflected in Figure 5.



Figure 4. Paste extrusion gun (a), filling tubular components (b), filled fabric tube (c), during the mycelium process (d), assembly of the soft pre-grown textile structure into the upside-down hanging construction (e/f), air dried dome from different perspectives (g/h) (Scott et al., 2022)

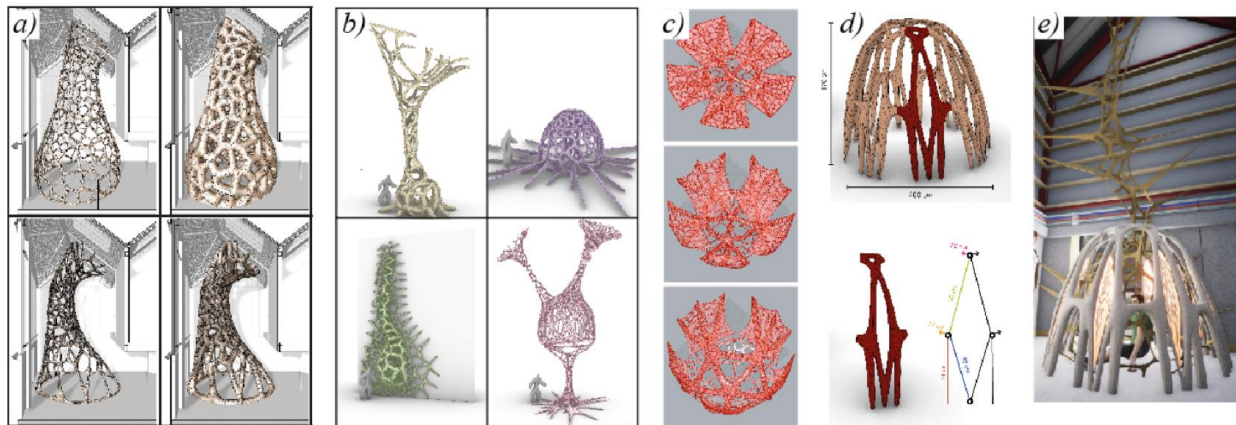


Figure 5. Initial structural permutations(a). Early bio-inspired morphologies (b). Topology from net to inverted dome (c). Modularisation of form for production (d). Visualisation in-situ (e) (Scott et al., 2022)

2.2. Industrial production

There are a few commercialized mycelium-based products in the literature, industrial reports and technical notes. Sun, Tajvidi, Hunt, McIntyre, and Gardner (2019) introduced two manufacturing methods of hybrid bio-composite made out of wood, mycelium and cellulose Nano fibers (CNF) as fibrous binders and matrices (Figure 6). As demonstrated in Figure 7, water absorption and consequent thickness swelling differ substantially in that clearly first type shows high water permeability and instability in water, which is a sign of poor initial bonding between wood and mycelium.

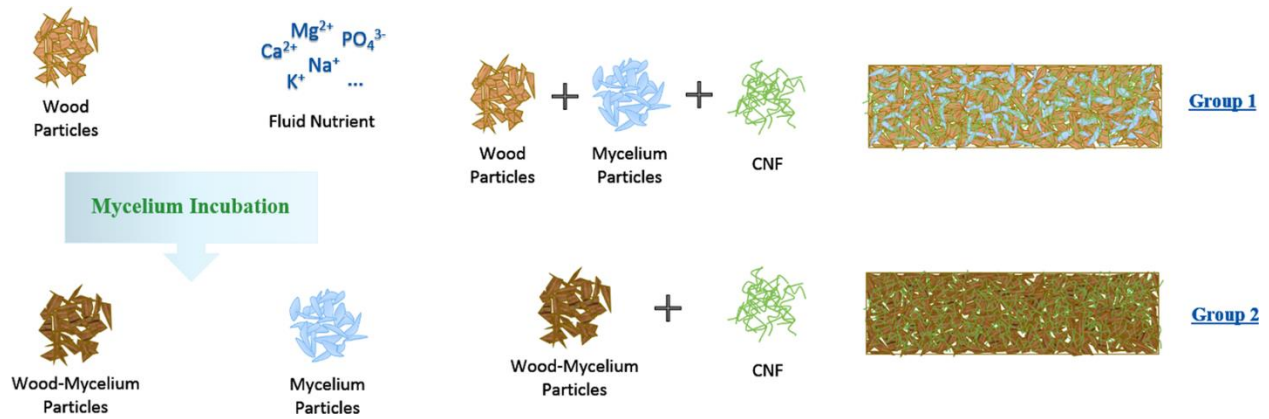


Figure 6. Two production methods of mycelium bio-composites offered by Sun et al. (2019)

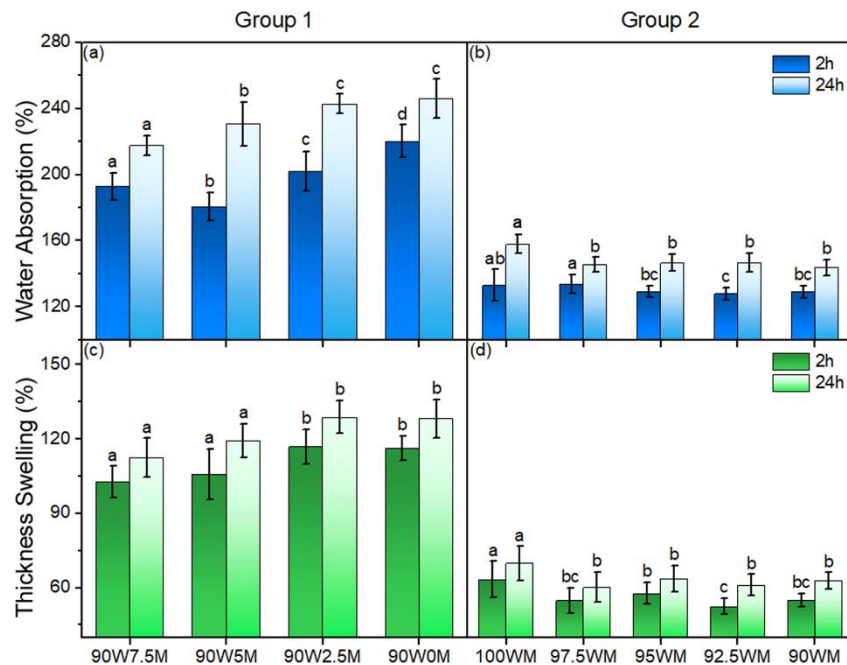


Figure 7. Water absorption (a,b) and thickness swelling (c,d) of Group 1 (a,c) and Group 2 (b,d) (Sun et al., 2019)

Jiang, Walczyk, McIntyre, Bucinell, and Tudryn (2017) described a method for manufacturing sandwich panels by use of mycelium as core, natural fiber textile (jute, hemp and cellulose) as skin, and a type of bio-resin as matrix. Stiffness and strength of the specimen are tested to realize how the choice of skin material and processing condition affects the mentioned performance parameters. The authors conclude that stiffness is dependent on the core strength, which is dominated by the colonization rate of the mycelium. Conversely, for the strength, the choice of skin is proved to be determining in the outcome. Moreover, a manufacturing process description is detailed for mycelium-based laminate structures in this article. According to Figure 8, step 1 to 3 are gluing, impregnation and integral tooling processes for laminate process and steps 4 to 6 are respectively filling with pre-colonized mycelium, growth phase, and drying process corresponding to typical processes of mycelium fabrication. Step 7 is also resin infusion, which is a standard part

of composite process. This article mostly focused on step 1 to 3 to check its feasibility to be included in the manufacturing process.

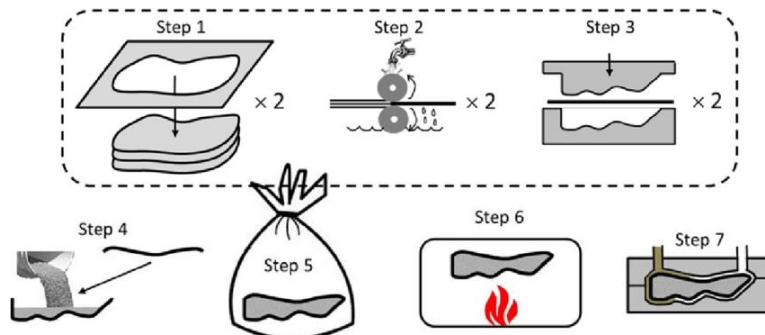


Figure 8. 7-step manufacturing process of mycelium fiber composites (Jiang et al., 2017)

In conclusion, by reviewing the influential parameters on fabrication process in the literature, different variables, which affect the quality of final product are shown in Figure 9.

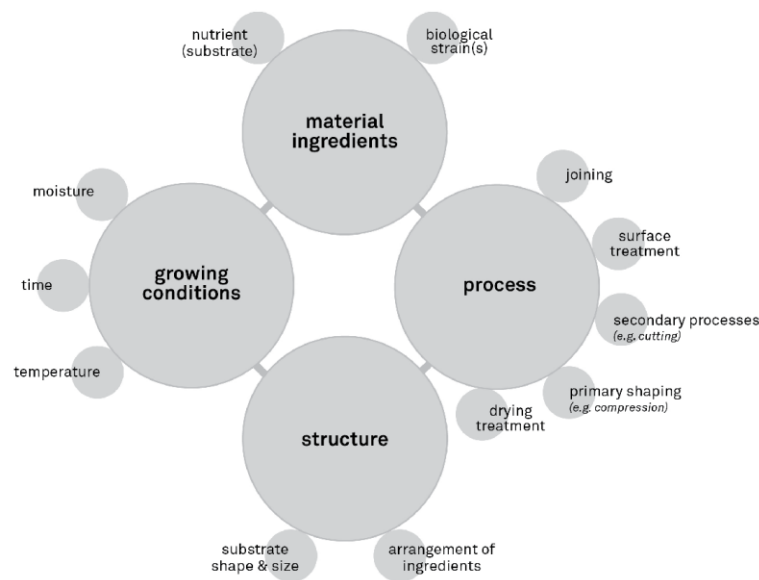


Figure 9. Fabrication parameters of mycelium bio-composite (Karana, Blauwhoff, Hultink, & Camere, 2018)

3. Mycelium mechanical and hygrothermal characterization

Both mechanical and hygrothermal properties of mycelium are rarely characterized in the literature. Based on the applied substrate and fungi type, numerous types of bio-composites could be developed, covering almost all of potential applications in different building components. Some of them are mentioned herein.

Islam, Tudryn, Bucinell, Schadler, and Picu (2018) characterized mechanical response of the material in response to cyclic compressive loads. A multiscale model is developed in this study as demonstrated in Figure 10. At micro scale, random fiber network is used as the model, whereas in macro scale, a continuum model is adopted and density variation is the investigated parameter to capture its rate of change. Non-linear behavior of material under compression is characterized in this study. Two continuum and random fiber models are successfully integrated together. The numerical results (right-hand side of figure 10) show an accurate agreement with experimental measurements.

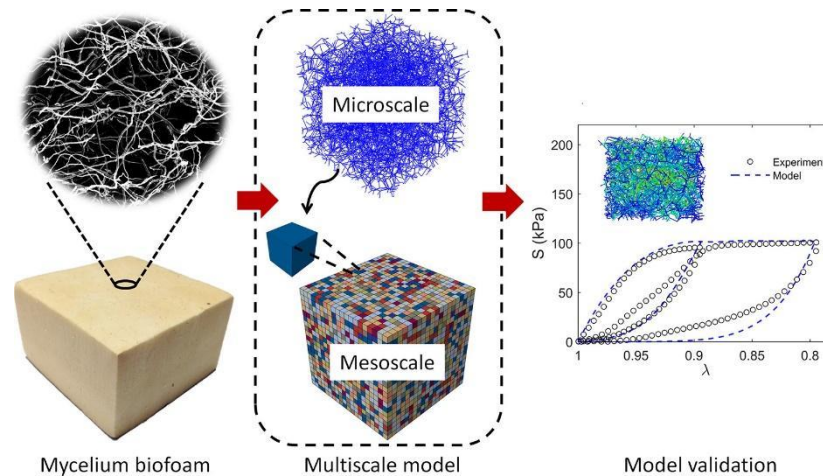


Figure 10. Schematic representation of multi scale model besides its validation with experimental results (Islam et al., 2018)

Karana et al. (2018) tested the tensile response of different types of mycelium subjected to several fabrication procedures and compared it with traditional materials depicted in Figure 11. Four reference materials including MDF, Palm, Cork, Styrofoam and Leaf are tested against six mycelium samples. The main difference is said to be rooted in processing techniques. For instance, foam-like samples in comparison with compressed material shows lower strength although they demonstrate good insulation performance.

Elsacker et al. (2019), in addition to characterization of mechanical strength, detailed absorption rate and thermal conductivity of some mycelium bio-composites (Figure 12). One of the highlights of this study is that the processing (loose, chopped, pre-compressed and tow) of the substrate is more dominant in shaping hygrothermal and physical properties rather than their chemical composition.

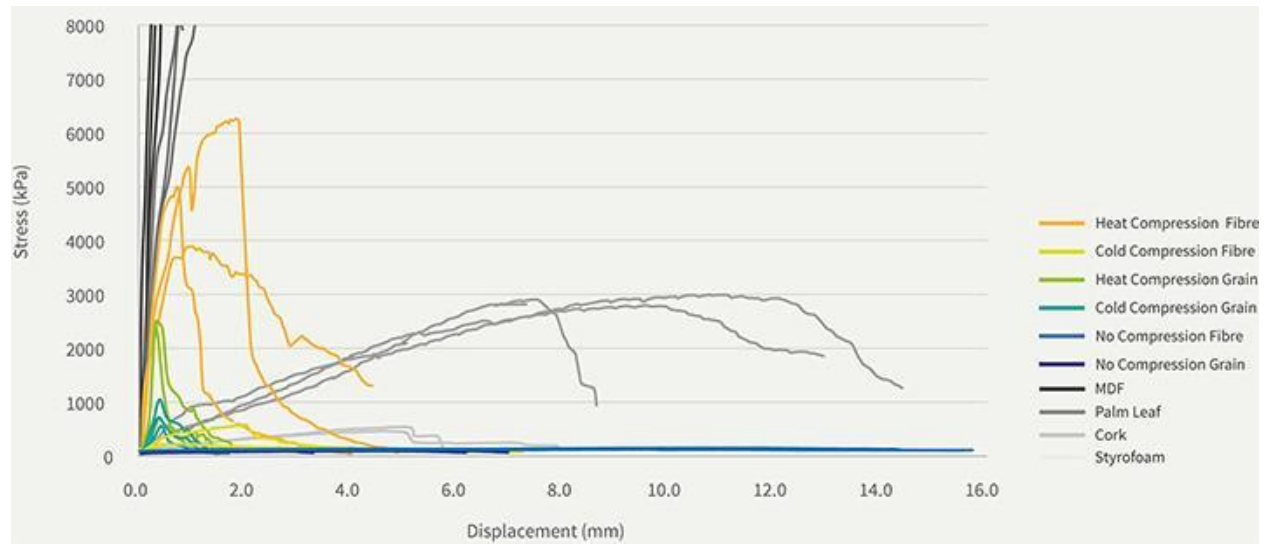


Figure 11. Tensile test results of mycelium composites in comparison to the reference materials (Karana et al., 2018)

With respect to thermal conductivity (Table 1), mycelium composites are shown to be well-fitted to insulation applications. In addition to better thermal performance, as mentioned in this study and explained in next section (life cycle analysis), they also represent a completely biodegradable material, which lowers end of life stage's emissions substantially.

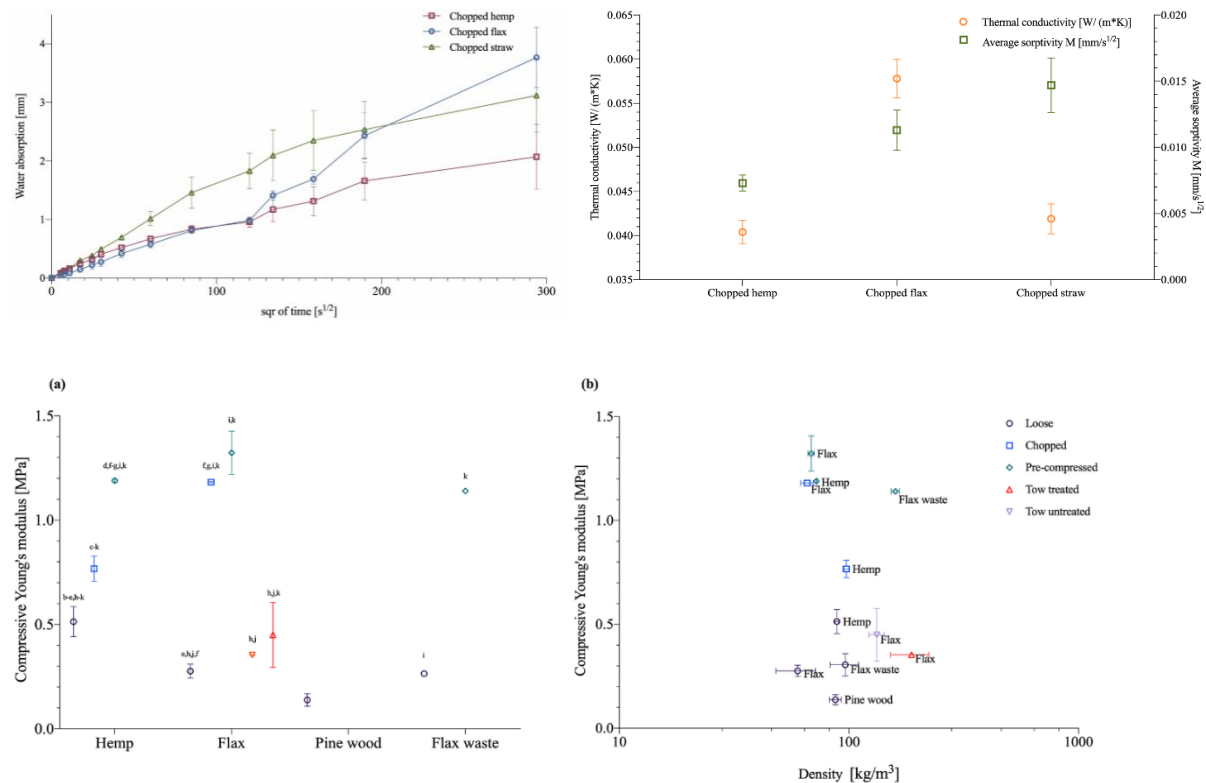


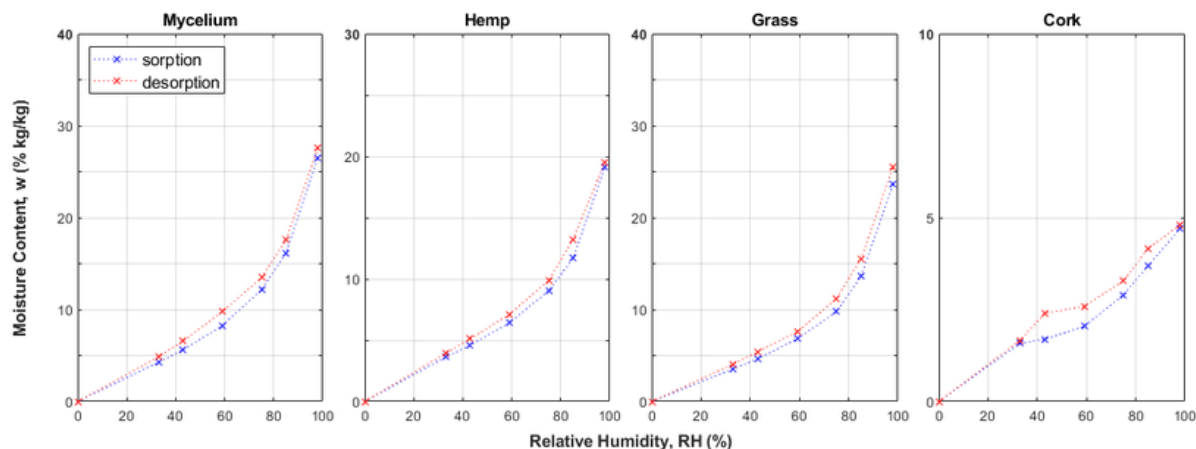
Figure 12. Hygrothermal and mechanical characterization of mycelium with different substrate processing (Elsacker et al., 2019)

Table 1. Comparison of mycelium bio-composite's conductivity with traditional insulation materials (Elsacker et al., 2019)

Insulating Material	Thermal conductivity [W/(m*K)]	Density [kg/m ³]
Mycelium-flax composite—a	0.0578 ± 0,002 ^{bc}	135
Mycelium-hemp composite—b	0.0404 ± 0,001 ^a	99
Mycelium-straw composite—c	0.0419 ± 0,0002 ^b	94
Rock wool	0.044	470–2250
Glass wool	0.033–0.045	13–100
Extruded polystyrene	0.025–0.035	18–50
Kenaf	0.034–0.043	30–180
Sheep wool plates	0.038–0.054	10–25

Concerning the hygrothermal characterization of mycelium, the sole study that proposes measurements of sorption isotherms and characterizes co-dependence of heat and moisture parameters is carried out by Koh, Gauvin, Schollbach, and Brouwers (Figure 13). For the specific composites in this study, the difference between sorption isotherms is minor, although based on the incorporated substrate each resulting composite needs to be characterized in terms of their sorption isotherms.

In addition to these graphs, co-dependence of thermal conductivity and relative humidity is plotted and linearized in Figure 14. In comparison between hemp, grass and mycelium they all exhibit nearly similar thermohygric performance on the mentioned plots, however cork has the lowest thermal conductivity and sorption properties amongst them.

**Figure 13.** Sorption-desorption isotherms for mycelium, hemp, grass and cork composites (Koh et al.)

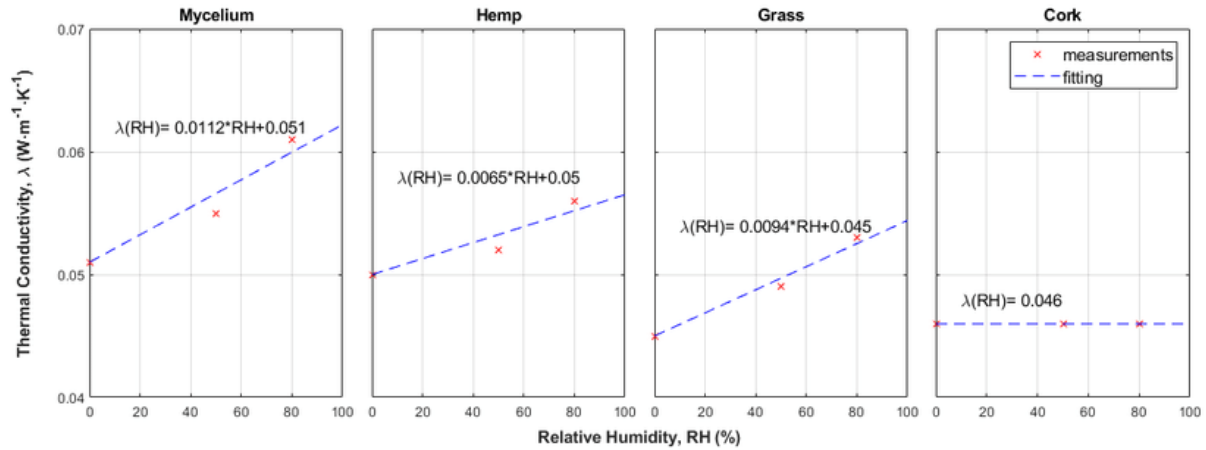


Figure 14. Thermal Conductivity λ against RH for mycelium, hemp, grass and cork composites (Koh et al.)

4. Life cycle analysis of mycelium-based composites

Using the concept of circular economy, which represents the minimization of both material and value along the entire supply chain, caused by the usage of mycelium in bio-based materials is reviewed in this section. EN 15804 (CEN (2012b)) defines life cycle stages, extending from raw material cultivation and harvesting to manufacturing, construction, operation, demolition and final disposal stage (Gorse et al., 2016; Jones & Brischke, 2017; Menet & Gruescu, 2012). Considering circular economy and choosing cradle-to-cradle boundaries (Figure 15) leads to the following stages defined under EN 15804.

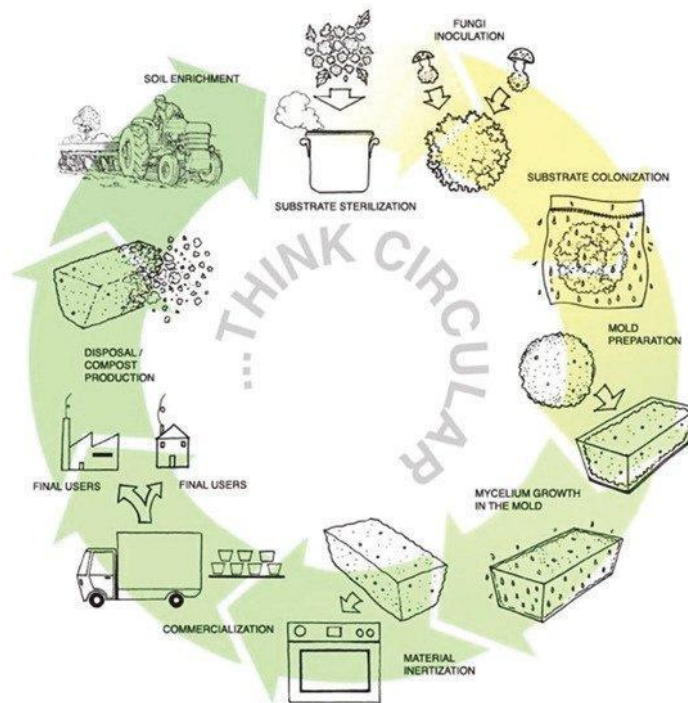


Figure 15. Diagram showing the production and life cycle of mycelium-based materials (Girometta et al., 2019)

4.1. Cultivation and Production

One of the detailed studies in the cultivation and growth stage of mycelium is conducted by Livne, Wösten, Pearlmutter, and Gal (2022) who elaborated on shorter life span of mycelium and its effect on the life cycle. Moreover, by taking timeframe of analysis into account, and subsequently capturing the effect of metabolic carbon of mycelium in life cycle analysis, the net embodied carbon resulting from fungi cultivation is proved to be reduced by 60%. Challenge of life cycle analysis in this stage, considering waste-based economy, is mainly co-production of materials. It is due to the fact that main plant and its waste serve different purposes. Although co-production essentially leads the system to contribute in circular economy, defining a reference scenario can be challenging since the purposes and outputs are not the same and different defined systems are diverging in some sense (Escobar & Laibach, 2021). To assess waste-based systems normally literature chose input-based life cycle analysis (Fieschi & Pretato, 2018; Garfí, Flores, & Ferrer, 2017; Seghetta, Tørring, Bruhn, & Thomsen, 2016).

4.2. Manufacturing

Since, there are only a few studies conducted on the assessment of mycelium's environmental impacts, reflecting a comparative analysis between traditional bio-based materials and mycelium-based composites is not viable with the current data of literature. For instance, functional unit that used to compare materials should be the same. However, in some studies the area of the wall panel is set as the functional unit, while in the others the U-value is chosen. Another problem is the substantial difference in the weight of mycelium bricks in the different papers, which avoids the study to compare different samples based on weight.

Stelzer et al. (2021) conducted a comprehensive life cycle assessment in fungal bricks and performed a comparison in both lab scale and "extrapolated" industrial scale fabrication of mycelium bricks. As practically there are no existing industrial plants in the study, some assumptions are made to customize the LCA into industrial scale. Furthermore, these two are compared with the other traditional building insulation materials. The results are reported in Table 2¹, and as can be seen, global warming potential (GWP) represents a considerable difference down to 6 times less GHG emission between mycelium bricks and traditional materials. Although lab scale fabrication does not reflect substantial variation with traditional materials, in terms of different environmental aspects (excluding global warming potential), mass production of these material is shown to be significantly more eco-efficient than other insulation materials. Yet, the main challenge is the difference between functional units of compared traditional building materials, with mycelium since the former type is mainly characterized by strength and resistance to weathering, whereas mycelium features insulation properties above all. This is due to the fact that there are not as much studies in the environmental impact assessment of mycelium. Another insightful conclusion of this study is the beneficial environmental effect of upscaling in the fabrication of mycelium from lab-scale to industrial scale, which is demonstrated in the lowest part of Figure 16. (Stelzer et al., 2021)

¹ The units for characterization factors including acidification, Eutrophication, Climate change, Land use, Water scarcity and smog in this study are respectively kg SO₂-eqv., kg PO₄-eqv., kg CO₂-eqv., Pt, m³ world-eqv. and NO_x-eqv.

Table 2. Comparison between categories of environmental impacts in mycelium bricks and other traditional building materials (Stelzer et al., 2021)

	Hemp shives based brick	Hemp shives based brick (scale up)	Facing brick	Sand lime brick	Concrete brick
Acidification	0,024	0,012	0,024	0,009	0,021
Eutrophication	0,015	0,013	0,004	0,002	0,004
Climate change	12,3	3,9	25,5	12,2	10,1
Land use	1110,0	1010,0	53,7	151,0	26,2
Water scarcity	0,552	0,374	0,545	0,808	0,747
Smog	0,015	0,006	0,030	0,013	0,028


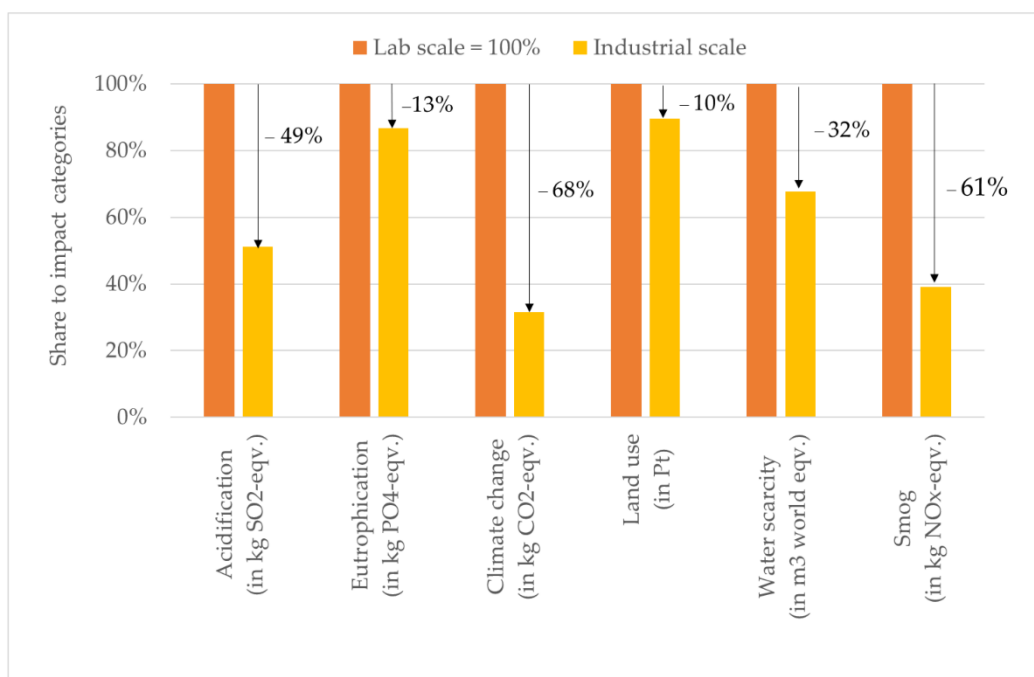



Figure 16. Reported difference between industrial and lab-scale production of mycelium bricks (Stelzer et al., 2021)

While the work of Stelzer et al. (2021) only represented the comparison of mycelium with traditional building material, Carcassi et al. (2022) compared the environmental impacts of a type of fungi brick with its other bio-based peers. The brick is composed of the waste of bamboo as the substrate called MycoBamboo by the authors. The functional unit (FU) is assumed to be a 1m² of each brick and the also the U-Value is set to be equal by changing the thickness of the samples.

As depicted in Figure 17, assuming 60 years storage period and considering the fuel source to be renewable, the global warming potential of mycelium bio-composite is reported to be lower compared to other bricks. However, the upscaling process from lab scale to industrial scale, and its effect on lowering global warming potential, although mentioned, is not discussed in detail. Besides, the end of life (EoL) scenario, which is pivotal in calculation of the environmental effects for mycelium bricks is not detailed and accounted for, in any of the two sources mentioned. An

important point mentioned in this study to justify the lower global warming potential of mycelium bio-composite is the replacement of synthetic binder in bio-based peers with fully natural and biogenic mycelium. The use of alternative low energy material to deactivate fungal growth is suggested as a means of reducing overall global warming potential of this novel technology (Carcassi et al., 2022).

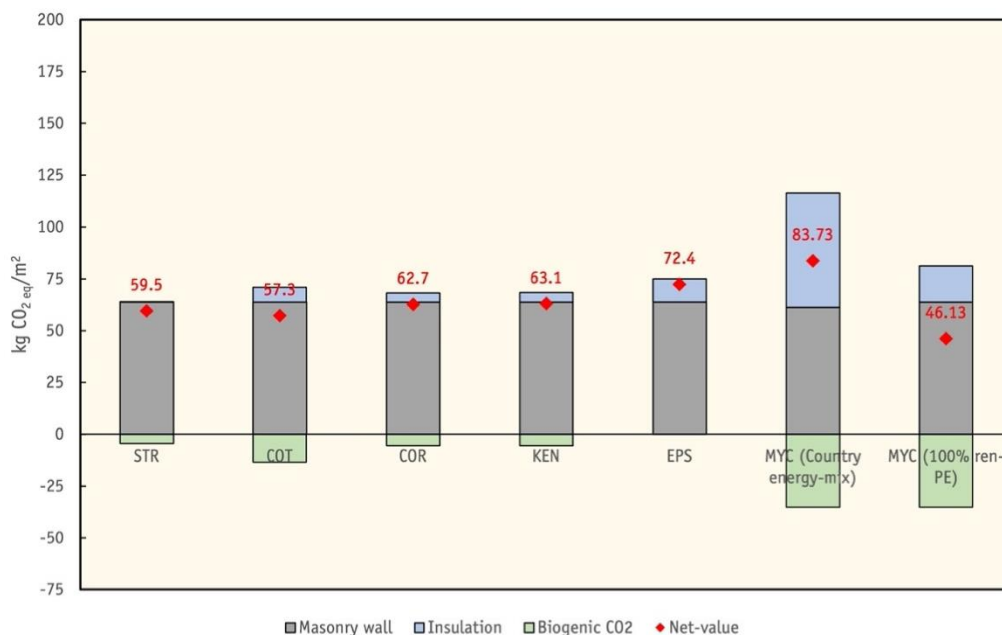


Figure 17. Comparison of mycelium bio composite with other bio-based peers (Carcassi et al., 2022)

4.3. Construction and Use Stage

In the construction phase, what should be noted is the capacity of bio-based building materials to be made onsite from local materials, and thereby major elimination of the emissions pertaining to transportation in long distances. The difference between newer generations of mycelium-based composites with the traditional bio-based materials is the existence of natural fungi binder as opposed to chemical binders in composites such as LHC. The necessity of natural binders will be pivotal in agricultural communities, which in turn lead to the circular usage of materials and wastes and substantial reduction of the emissions related to usage of non-locally produced materials.

In Canada and Europe, we observe such arrangements, which continue to be put in place. In France, a new environmental regulation (RE2020) is issued, providing regulatory basis for the usage of bio-based alternative building materials for a future sustainable construction. In an article in www.architectural-review.com there are interesting statistics that pertain to the growth of bio-based construction in France. The main point is the abundance of straw as a bi-product of wheat cultivation in France, which produces up to 25 million tons year, of which only 10 percent is reported to be enough for the insulation of 500,000 dwellings per year. Besides that, France is also the leading producer of hemp in Europe, as another substrate for bio-based materials (www.architectural-review.com). The innovation in using mycelium as the binder and additional fibrous structure is a transformation in the supply chain of bio-based materials since it enables the

both construction and renovation sector to use fully-local materials, given the abundant substrate and fungi resources in Canada and France. Modular construction as a resulting construction paradigm is reportedly producing substantial less greenhouse gas emission in the construction phase of life cycle (Boafo, Kim, & Kim, 2016). This growing practice contributes in different industries from construction and renovation to packaging and fashion. In the renovation sector, since mycelium bricks are easy to produce and install there is a growing market in Europe, which is extending to the North America in the recent years.

Use phase stage of lifecycle, in terms of environmental impacts, typically dominates all other stages throughout cradle to grave boundaries. That is mainly rooted in high magnitude of energy consumption in this phase, which is consumed to satisfy heating, air conditioning, electricity, and hot water needs of residence. The role of mycelium-based insulation materials in this phase is their considerable insulation capacity, which substantially decreases building's energy loss and consequent environmental impacts in some cases by 50% (Livne et al., 2022).

4.4. End of Life Stage

In this phase, since mycelium bio-composites among bio-based materials in general do not have a long background, end of life scenarios are not assessed in practice. Therefore, studies are based on assumptions and most of them consider different end of life scenarios (Lecompte, Levasseur, & Maxime, 2017). Two distinctive processes and scenarios are mainly covered in the literature, including recycling and disposal. One of the popular disposal processes, which has been surveyed in the literature, is incineration. The reason lies in the fact that most bio-based materials are combustible, and incineration could provide efficient energy recovery solutions (Wojnowska-Baryła, Kulikowska, & Bernat, 2020).

Beigbeder, Soccalingame, Perrin, Bénézet, and Bergeret (2019) examined four scenarios of landfilling, incineration, compositing and recycling. As illustrated in Figure 18, recycling scores higher among other alternatives in terms of environmental impacts (fresh water eutrophication excluded), except for bio-based plastic polymers, for which it is costly to perform. As such, second choice is incineration and in other cases composting. As for incineration, resulting combustion substances could cause hazardous phenomena such as soil eco toxicity and climate change. Utilization of municipal incineration is suggested as an efficient approach because of either particular burdens of this equipment, or the mixture of bio-based and non-bio-based substances in the waste material. It results in saving fossil fuels for heat and electricity generation, especially when systematic exploitation of them happens within the framework of CHP systems in integrated neighborhood (Jones & Brischke, 2017).

Pittau, Krause, Lumia, and Habert (2018) investigated the effect of storing carbon in biogenic materials and lime-based products when they are used as construction material, particularly in exterior walls. The novelty of this research is considering the timeframe of emission and carbon sequestration, which in turn leads to different results compared to those assuming emitted and sequestered carbon as net zero. The results show that storing carbon in fast-growing biogenic materials is more efficient than in timber elements. The carbon stored in fast-growing biogenic materials is fully captured by crop regrowth only one year after construction; whereas a longer time is expected for forest products due to the long rotation period required for forest regrowth. For other compostable bio-based materials, most common reported end of life scenario in the literature is landfilling. Its major consequences are categorized as land use pertaining issues, climate change, and eco-toxicity (Fouquet et al., 2015). Besides, anaerobic decay of this type of

materials (esp. wood, cork, and paper) is incomplete; and leads to long-term storage of carbon in landfills.

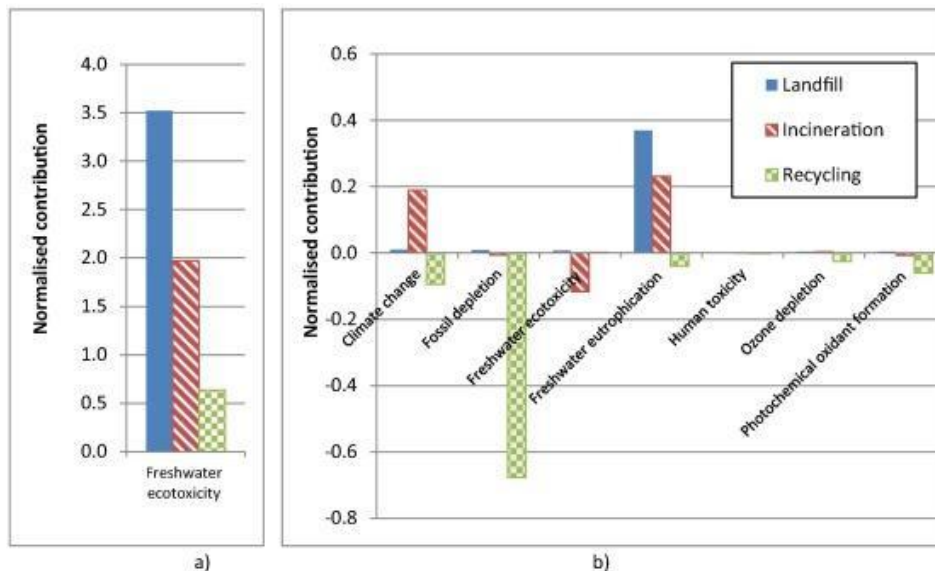


Figure 18. Environmental impacts of bio-composites (Beigbeder et al., 2019)

However, mycelium bio-composites requires a different approach due the 100% degradable compound. Cascione et al. (2022) investigated circularity in bio-based panels through calculating the impacts of different parts of the wall panel, and sought after low impacts alternatives, one of which is mycelium composite as insulation. The end of life scenario is assumed to be landfilling, since it is completely biodegradable, but it is asserted that since it contains fibers, a small percentage of the wastes could be also incinerated. Landfilling is tied to the context of carbon sequestration, which is a process of utmost importance in the end of life scenarios. Besides this study, there are not cradle-to-cradle LCA studies for mycelium, especially those studying the possibility of reusability and recyclability of these materials. Further, durability of these materials over time has yet to be questioned, since it is still a new technology and is not vastly incorporated in buildings.

5. Intersection between art, science, engineering and design in bio-based engineering

Recently some applications of mycelium is employed by artists. The intersection between art and nature-based technologies is an interesting rising trend in the studies and related projects. With the onset of new generations of nature-based construction solutions, which are “grown” inside molds there is a new opportunity for designers to produce their own building materials. Abstract structures that were previously infeasible to be built in real scale projects, now begin to be fabricated and promoted in the modern construction community. The new opportunity of including art in novel sustainable solutions provides a unique possibility to enhance the quality of life in nature-based houses built by collective contribution of engineers and artists. In this last section of the paper, some of these projects are reviewed.

In addition, cutting-edge knowledge is integrated with these artistic perspectives in bio-based context, creating exceptional projects, which are currently under development. In this context, art acts as expression, science as exploration, engineering as invention and design as communication. The input from one domain becomes the output for another domain. “*Science converts information*

into knowledge, Engineering converts knowledge into utility, design converts utility into cultural behaviors, art is taking that cultural behavior and questions our perception of the world". (Dadich et al., 2019). A brilliant example of this paradigm, is the works of MIT Media Lab (Bader et al., 2022; Inamura, Stern, Lizardo, Houk, & Oxman, 2018; Kayser et al., 2018), wherein cutting-edge research are being conducted, some of which is constructed as proof of concepts ("<https://oxman.com/projects>,"). In the Silk Pavilion project (Figure 19), a brilliant co-fabrication system is demonstrated. The concept is for human nature to “co-habit and co-fabricate at the same time (Dadich et al., 2019)” and “growth as opposed to assembly” which is the same paradigm as the context of mycelium bio-composites.



Figure 19. Silk Pavilion spun by silkworms ("<https://oxman.com/projects>," ; <https://www.dezeen.com>)

Another bio-based project is Aguahoja (Figure 20), a bio-based high-tech structure made of components including cellulose, chitin, and pectin, same materials found in trees, crustaceans and apple skins. Chitin, for instance, is found in the form of thin, transparent dragonfly wings, as well as in the soft tissue of fungi. Cellulose makes up more than half of plant matter planet-wide. *“These materials, and the living systems they inhabit, outperform human engineering not only through their diversity of functions but also through their resilience, sustainability, and adaptability”* (["https://oxman.com/projects,"](https://oxman.com/projects)). The Aguahoja demonstrates a material alternative to plastic, by transforming the toxic waste cycle through the creation of biopolymer composites. Another innovation of this project is a *“robotic fabrication platform, engineered to convert cellulose, chitosan, pectin, and other abundant biopolymers, into high-performance sustainable hydrogels that can be 3D printed into objects for applications spanning scales from millimeters to meters”*. (["https://oxman.com/projects,"](https://oxman.com/projects))

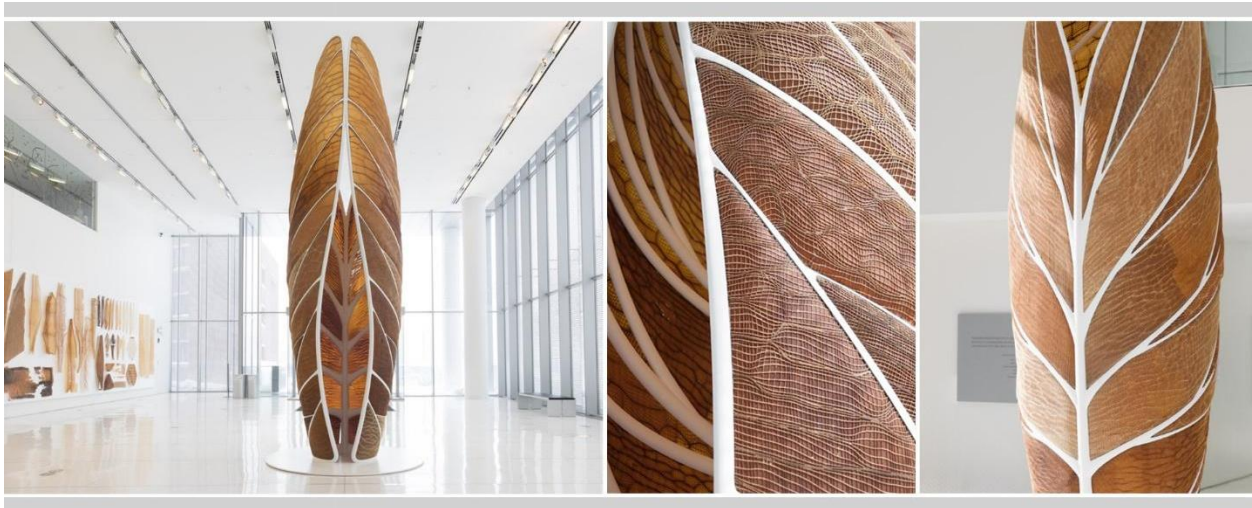


Figure 20. Aguahoja project demonstration (<https://www.cntfactory.com/2019/05/14/aguahoja-programmable-water-based-biocomposites-digital-design-2/>)

One of the initiatives that introduces mycelium in the building industry is the growing pavilion project (Figure 21), recently constructed in Floriade Expo 2022 as well as at the Dutch design week. *“The 10 ton CO2 negative and 95% circular structure is made up of five grown core raw materials: wood, mycelium, residual flows from the agricultural sector, bulrush (cattail) and cotton. Showcasing each material as raw as possible, the pavilion has a very distinctive visual identity, organic texture and color. It stands as a necessary and viable solution for reducing the use of fossil resources and its destructive impact on climate change. Inside the pavilion offers visitors a storytelling experience, taking them on a bio-based journey of what is already possible but also what the near future will bring. The Growing Pavilion is a catalyst, starting, sharing and driving the conversation about bio-based building that is essential to achieve the desired change in our thinking and doing”*. (["https://floriade.com/en/at-the-expo/national-pavilions/mycelium-parc/,"](https://floriade.com/en/at-the-expo/national-pavilions/mycelium-parc/) ; ["https://thegrowingpavilion.com/about/,"](https://thegrowingpavilion.com/about/))



Figure 21. Growing pavilion in Dutch design week (<https://www.dezeen.com>)

6. Discussion

This section is proposed in an attempt to link all of the above reviews and extract their common trends, results and conclusions. It is divided into two sections: impacts and current applications and viability.

6.1. Impacts

Mycelium as a root-like fungi structure is one of the promising innovations in transforming building materials into new net-zero emission types. Throughout all life cycle stages, incorporation of mycelium substantially decrease the GHG and energy emissions. In retrospect in traditional bio-

based materials, using agricultural products could cause environmental downsides of acidification, eutrophication, etc. Conversely, as mycelium's emerging industry is becoming more prone to using agricultural waste as the base material, rather than the main products, long term mentioned environmental burdens would be highly compromised. Besides, by replacing chemical agents and binders in previous generations of bio-based materials with natural mycelium, toxic and energy-intensive production processes are transformed. Supply chain management plays a pivotal role in fabrication of mycelium composites, to institutionalize the usage of locally produced agricultural waste and balanced supply and demand, especially in the remote and rural communities. The main idea in the production of mycelium bio-composites is not merely to focus on the main substances to be made or grown naturally, but also is to utilize bio-based (and low-emission) compounds, agents and binders to achieve zero emission levels. Biodegradability of this material is critical to decrease subsequent emissions especially in end of life cycle stage. However, this property could cause other downsides pertaining to possible low durability in long-term usages. Therefore, there is a trade-off here, which needs to be addressed in the literature. To the knowledge of author, no specific studies covered this topic as of now.

In the life cycle assessment critical debates in the literature mostly involve the following issues. The electricity consumption is a tricky parameter included in the assessment of GWP, in that depending on the burnt fuel for electricity generation, consequent impact will vary considerably. Releasing stored biogenic carbon, as a result of burning biogas for electricity generation is a game-changer in environmental impacts, compared to burning fossil fuels. Another point is the upscaling the fabrication process into mass production and its details leading to the reduction in environmental burdens, for example diminishing the consumption of plastic bags, decreasing the emissions of sterilization process, etc. Since, there are not elaborate and detail studies on environmental impacts of mycelium bricks' manufacturing plants, the LCAs are based on assumptions rather than detailed technical facts. Finally, although there are comparison between different produced bio-based materials, some of which are presented in this study, due to the varying applications and accordingly different functional units, it is complicated to illustrate an accurate comparison between their impacts. Therefore, the discussions are roughly made to envision and calculate the impacts of the progressive path in the evolution of mycelium. The role of traditional binders in environmental impacts and the effect of their replacement with fibrous mycelium web is not observed in the literature. In addition, the GWP of novel manufacturing processes in the fabrication of mycelium bricks, such as hot press is not reported in the current literature, to the knowledge of authors. Most important studies on the impact analysis are summarized in Table 3.

Table 3. Studies on the environmental impacts of mycelium and other bio-based materials

Author and Year	Field of study	Application and details
(Stelzer et al., 2021)	LCA	Comparison of LCA in lab-scale and industrial scale
(Livne et al., 2022)	LCA	Time-oriented life cycle analysis
(Escobar & Laibach, 2021)	LCA	Review

(Carcassi et al., 2022)	LCA	Replacement of synthetic binder with biogenic mycelium
(www.architectural-review.com)	Supply chain	Supply chain of agricultural products in context of circular economy
(Boafo et al., 2016)	LCA	Modular construction's LCA
(Lecompte et al., 2017)	LCA	GHG emission and capture
(Beigbeder et al., 2019)	LCA	Bio-composite's end of life scenario
(Pittau et al., 2018)	LCA	Biogenic carbon and carbon sequestration
(Cascione et al., 2022)	LCA	LCA in circular design

6.2. Physical characterization and production practices

Many of thermo-hygric properties of mycelium composites are covered in the literature, which are reviewed in this study. Three parameters of substrate type, fungi and fabrication process create the final properties based on the studies. This review revealed that thermal insulation of mycelium is equal or higher than non-bio-based and bio-based peers, mostly due to its high porosity. In addition, concerning hygric properties, water absorption and moisture buffer of this material is considerably higher than other insulation materials. The trade-off of moisture buffer is discussed in some of the cited studies; although moisture buffer directly enhances the thermo-hygric and comfort condition of indoor condition, high moisture results in shrinkage of material, fungal growth and less durability. Fungal growth on this type of insulation is modeled in some of the studies, and their results reveals that with incorporation of some of the developed composites as insulation materials, fungal growth is manageable.

Regarding processing techniques, numerous parameters are mentioned in the fabrication procedure, which affect the performance of material. Type of substrate processing, methods like hot and cold pressing, incorporation of other living organisms such as bacteria, air feeding the growing structure and usage of scaffold structures are mentioned as fabrication parameters, each of which could be customized based on the required technical specification. That said, due to the variety of resulting developed materials, there is a need for further technical characterization for the customized composites, in order to clarify the effect of the above-mentioned parameters on the physical properties. In contrast to the insulation applications, there is not an observed load-bearing and structural application for any mycelium-based composites in the literature and cited industrial projects. However, in terms of present scalable solutions, even non-load bearing technologies are not commercialized yet to be vastly supplied to the construction industry. The case studies in most of the researches are small-scale buildings. Studies on hygrothermal and mechanical characterization are listed in Table 4.

Table 4. Studies on the technical characterization of mycelium

Author and Year	Field of study	Application and details
(Elsacker et al., 2019)	Characterization	Mechanical and hygrothermal characterization
(Islam et al., 2018)	Characterization	Mechanical characterization in response to cyclic compressive loads
(Karana et al., 2018)	Characterization	Mechanical characterization in response to tensile stresses
(Koh et al.)	Characterization	Hygothermal characterizaiton of mycelium including sorption isotherms
(Girometta et al., 2019)	Characterization	Mechanical and hygrothermal characterization

6.2. Current applications and viability of mycelium in buildings

A highly scaling and progressive trend is observed in bio-based technologies. This trend is not merely limited to mycelium, but it spans a wider spectrum. From phase change material to hydrogels and algae-based technologies, and in other perspective from bio 3D printers to self-sufficient robotic and swarn-based manufacturing, there are numerous under development solutions to neutralize embodied carbon emission of materials. Bio-based materials are being developed, not only in buildings but also in vast range of industries from FMCG to automotive, aerospace and fashion as observed by authors. Nonetheless, mycelium has a pivotal role in new generation of bio-based materials as a substance, which enable the material to be grown instead of being manufactured. This growth mechanism of fabrication is observed in almost all of the cited cutting edge projects. Reviewed studies on the novel production practices of mycelium and other bio-based materials, as well as the state-of-the-art bio-based technologies are presented in Table 5.

Table 5. Studies on mycelium's production practices and novel bio-based technologies

Author and Year	Field of study	Application and details
(Stelzer et al., 2021)	Production practice	A three step production practice
(Appels et al., 2019)	production practice	Influence of fabrication factors on hygrothermal, mechanical and visual features
(Attias et al., 2019)	production practice	Influence of fabrication factors on hygrothermal, mechanical characteristics
(Scott et al., 2022)	production practice	Integration of mycelium and bacterial cellulose

(Sun et al., 2019)	production practice	Industrial manufacturing practice of hybrid bio-composites
(Jiang et al., 2017)	production practice	Industrial manufacturing practice of sandwich panels using mycelium and resin
(Karana et al., 2018)	Design and production	A case study on designing (with) mycelium-based materials
(Dadich et al., 2019)	Art and science	A documentary of Neri Oxamn in MIT Media Lab
(Bader et al., 2022)	Art and science	3D glass printing
(Inamura et al., 2018)	Art and science	3D glass printing
(Kayser et al., 2018)	Art and science	Swarm-based robotic system
("https://oxman.com/projects,")	Art and science	- Silk Pavillion project - Aguahoja project
(https://www.dezeen.com)	Art and science	- Silk Pavillion project - Growing Pavillion project
("https://thegrowingpavilion.com/about,")	Art and science	- Growing Pavillion project

Practicality and scalability is the major bottleneck of recent technological advancements. As for building materials in specific, what is seemingly occurring is that merely traditional solutions such as hempcrete (LHC) began to scale in the construction industry and TRL of other technologies are still in prototype demonstration level. The pivotal role of mycelium could be in scaling-up of the bio-based materials. This scalability is not only defined in terms of mass production, but also in extending the mycelium's usage to other applications and industries, some of which are reflected in Figure 22. Although undeveloped building standards directly affect the less usage of such materials, the role of researchers in communicating the idea of using these sorts of technologies in the industry is of utmost significance.

materials and corresponding applications are very limited. Regarding the physical characteristics, there is a strong correlation between the combination of straw, fungi and processing method with the final hygrothermal and mechanical properties. Mycelium's thermal insulation and hygric capacities are proved to be efficient in the literature, whereas its mechanical performance in load-bearing applications is not satisfactory. Cutting-edge researches in the field of nature-based materials shows an emergent path in the reconciliation of art, science, design and engineering. Accordingly, some of scientific groups and their most recent projects are cited to envision the progressive trend of the development of this category of material in the construction applications.

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