Fungal Foundations & Futuristic Finishes

Using Bio-Finishes to Protect Mycelium Based Construction Materials from Decay

Writing Assignment
Bio Inspired Innovation

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Laymen summary

Our current ways of production, consumption and trade are dangerously unsustainable and cause environmental issues. This is why a shift to a more sustainable, circular economy is necessary. To achieve this, resource use needs to be more efficient and environmentally friendly. Mycelium materials are very versatile and contribute significantly to this shift. They are made from completely renewable resources and they are biodegradable, so they do not cause pollution. They have characteristics that make them very suitable replacements of plastic packaging for example, but they can also be used in construction work. To protect them from weathering and decay, they need protective coatings. Most conventional coatings are made from non-renewable resources like petroleum and are toxic to the environment. In this literature research, different bio-based coating materials to potentially shield the mycelium materials are looked into.

Abstract

The current dominant economic development model, "take, make and dispose", is not only jeopardizing the economic stability, but also the integrity of the natural ecosystems upon which humans depend for survival. There has long been a demand to put strategies for sustainable development into action as resources are being depleted. The production of synthetic materials depends heavily on nonrenewable resources such as petroleum and handling these materials at the end of their life cycle poses more waste issues every day. Reducing resource use and lowering the ecological footprint is therefore a must and the paradigm shift to a circular economy needs to be made. Mycelium materials contribute significantly to this paradigm shift as they obtain traits that make them practicable alternatives to many synthetic materials in both economic and environmental fields. They can even be used in construction work. The idea of using mycelium materials for temporary structures is being explored by various artists and designers. To protect the mycelium materials used in construction from decay, protective coatings are needed, especially with the outlook on long-term use. As most synthetic polymers rely on nonrenewable resources and are not sustainable, a variety of bio-based polymers was looked into in this research. As all of the assessed bio-based polymers have desirable properties, their drawbacks and possible solutions have also been discussed.

1. Introduction

The most important global patterns of production, consumption and trade are alarmingly unsustainable in our economy (Preston, 2012). Petroleum reserves and other non-renewable resources are being depleted and waste management is facing problems (Jones et al., 2017). "Take, make, and dispose" is the current dominant economic development model, which is not only jeopardizing the economic stability, but also the integrity of the natural ecosystems upon which humans depend for survival (Ghisellini et al., 2016; Ness & Ness, 2010; Park & Chertow, 2014). Industries have been calling for guidance in putting strategies for sustainable development into action for a long time now (Murray et al., 2017).

The production of synthetic materials requires nonrenewable resources such as petroleum, or they are harvested from limited natural resources (Jones et al., 2017). Moreover, handling of these materials at the end of their lives poses problems with respect to sustainability. For example, in Australia only 14% of disposed plastic is recycled, because from an economic point of view the value of plastics is not high enough to justify recycling (The Allen Consulting Group, 2009). Often synthetic waste is disposed in landfill (depots), which releases toxic elements and greenhouse gases. When looking at the total amount of greenhouse gases emitted due to waste management, 75% originates from landfill disposal. Of this 75%, 55% is methane, a gas that has a global warming potential that is 21-25 times higher than that of carbon dioxide (Boucher et al., 2009; The Allen Consulting Group, 2009). Another big factor in both the energy consumption and waste management problem are building materials. In the USA only, 40% of the landfill can be traced back to construction and demolition (Dougoud et al., 2018).

The eventual goal is to lower resource use, and thus to reduce the ecological footprint, but still achieve the necessary economic growth (Ness & Ness, 2010). This is why conversion to a circular economy is of great importance. The goal of a circular economy is to increase the efficiency of resource use. By forming closed loops (creating circularity) of material and energy use, the industry's impact on the environment will be curtailed. As a result, an improved balance and harmony between economy, environment and society will be achieved (Ghisellini et al., 2016; Posch, 2010). In order to achieve this goal, resources have to be substituted by renewable, bio-based materials (Cerimi et al., 2019; Dahiya et al., 2020). Bio-based materials are derived from molecules or structures of microbes, plants, macro-algae and animals (Appels et al., 2018). Substituting nonrenewable and naturally limited resources by bio-based materials will benefit the environment. It would reduce emissions, virgin material use and waste generation (Posch, 2010). Some examples of bio-based materials are plant-derived thermoplastic starch (Averous et al., 2000), bacterial-derived polyhydroxyalkanoic acid (Babu et al., 2013) and fungal mycelium (Cerimi et al., 2019; Haneef et al., 2017; Islam et al., 2017; Jiang et al., 2016). Especially fungal mycelium materials contribute significantly in the shift to a circular economy and has been a popular topic of research recently.

Mycelium is a network of hyphae that is formed by filamentous fungi when colonizing substrates (Appels et al., 2018; Papagianni, 2004). Mycelium composites resort to biological growth instead of production processes that are both expensive and highly energy consuming. They require macronutrients (such as carbon, oxygen and nitrogen) and micronutrients (such as iron and zinc) to grow, which can be found in organic waste for example (Islam et al., 2017; Jiang et al., 2016; Jones et al., 2017). Moreover, they can grow in all shapes and sizes, and to fill complex geometries. Disposal of mycelium composites does not come with any costs or pollution, because they are innately biodegradable (Jones et al., 2017). These traits make them practicable alternatives to many synthetic materials in both economic and environmental fields. Mycelium materials can also be used in construction work. It is a material that performs well structurally, has minimal impacts on the environment and can seriously increase the sustainability of a building (Cerimi et al., 2019; Dougoud et al., 2018; Jones et al., 2017). Mycelium bricks have already been brought to practice. For example by David Benjamin, who did a project called *Hy-Fi* (fig. 1a) (Peters, 2015), and by Philip Ross, who did a project called *Mycotectural Alpha* (fig. 1b). Hy-Fi was a temporary summer pavilion that consisted of bricks that were a 100% biodegradable and compostable, made from farm waste, mycelium and corn stalks (Peters, 2015). The *Mycotectural Alpha* was a teahouse that consisted of 500 bricks in which mycelium and sawdust were used. It was on display for an exhibition in the Düsseldorf Kunsthalle before the bricks were taken to boil and served as a herbal tea to the guests (Jones et al., 2017; McGaw, 2018).

Figure 1. Examples of mycelium-based construction materials. (**A**) Hy-fi organic compostable tower (left image: LafargeHolcim Foundation; right image: krisgraves). (**B**) Mycotectural Alpha teahouse (courtesy of Philip Ross). Obtained from Jones et al., 2017.

Since mycelium bricks (bio bricks) are entirely biodegradable, something has to protect the material from being broken down by microbes, especially when these materials become moist. Besides, insects can feed on the mycelium bricks. As an illustration, it is known that honey bees feed on mycelia to reduce viruses in the populations (Naeger et al., 2018). To avoid microbial growth, attract insects and reduce fungal smell, the bricks have to be coated. The aim of this thesis is to assess which bio coatings are available and which of those are the best option to create bio bricks with a long lifetime; only degrading when they are shredded. First the subject of mycelium materials will be touched upon, in particular which species and substrates are used. This will be followed by describing the different types of bio-coatings that are available. Next, I will discuss what the best bio-coating will be for the fungal materials including research recommendations.

2. Mycelium materials

2.1 Mycelial architecture

Mycelium-based composites are a product of the growth of filamentous fungi on organic materials, such as agricultural waste streams (Appels et al., 2019; Haneef et al., 2017). Hyphae are composed of elongated cells, which are compartmentalized by septa (Bonfante & Genre, 2010; Haneef et al., 2017) (fig. 2). The surface of hyphae consists of the cell wall (fig. 2C). The cell wall protects the hyphae (Papagianni, 2004) and contributes to strengthening the mycelium as a whole (Haneef et al., 2017; Islam et al., 2018; Vega & Kalkum, 2012). Moreover, it defines the fungal shape (Thomson et al., 2015) and interacts with the (a)biotic environment, for instance by adhering to a substrate (Ehren et al., 2020). The cell wall comprises different components (fig 2C and 3) as is illustrated by the cell wall composition of the model basidiomycete *S. commune* (Ehren et al., 2020). It consists of a relatively rigid and mobile layer. The rigid part contains chitin and β-(1,3)-(1,6)-glucan (Ehren et al., 2020; Sietsma & Wessels, 1979, 1981) as well as α-(1,3)-glucan and polymeric fucose (Ehren et al., 2020). The mobile part of the cell wall also contains β-(1,3)-(1,6)-glucan, but also β-(1,6)-glucan, β-(1,3)-glucan, α-glucan and polymeric mannose (Ehren et al., 2020). A similar buildup of the cell wall was shown for the ascomycete *Aspergillus fumigatus* (Kang et al., 2018), suggesting that higher fungi have a similar cell wall architecture.

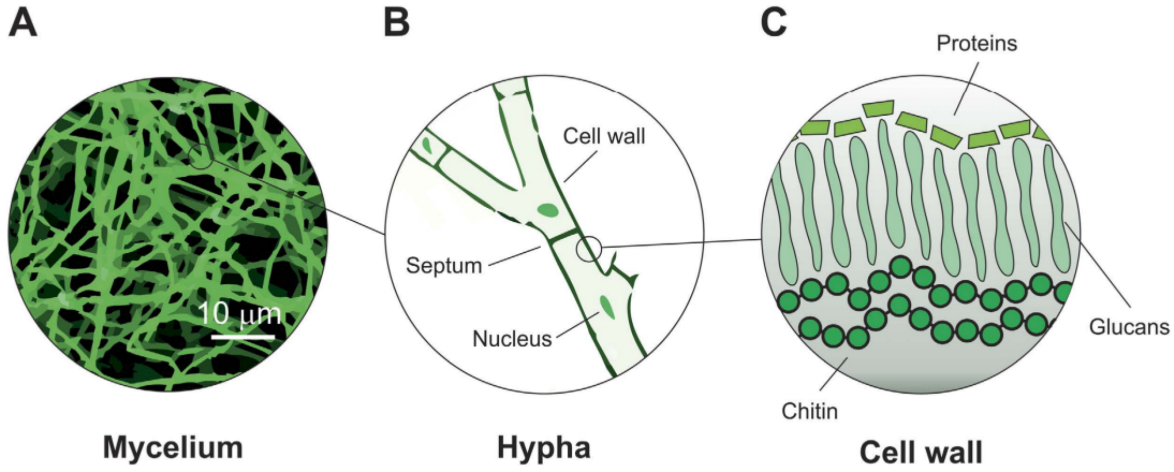

Figure 2. Schematic representation of mycelium physiology at different scales. (**A**) Optical microscopy image of a mycelium film showing branched network of micro-filaments (hyphae). (**B**) Schematic representation of a hypha that is formed by cells separated by cross walls (septa), all enclosed within a cell wall. (**C**) Schematic representation of the fungal cell wall. Taken from Haneef et al. (2017).

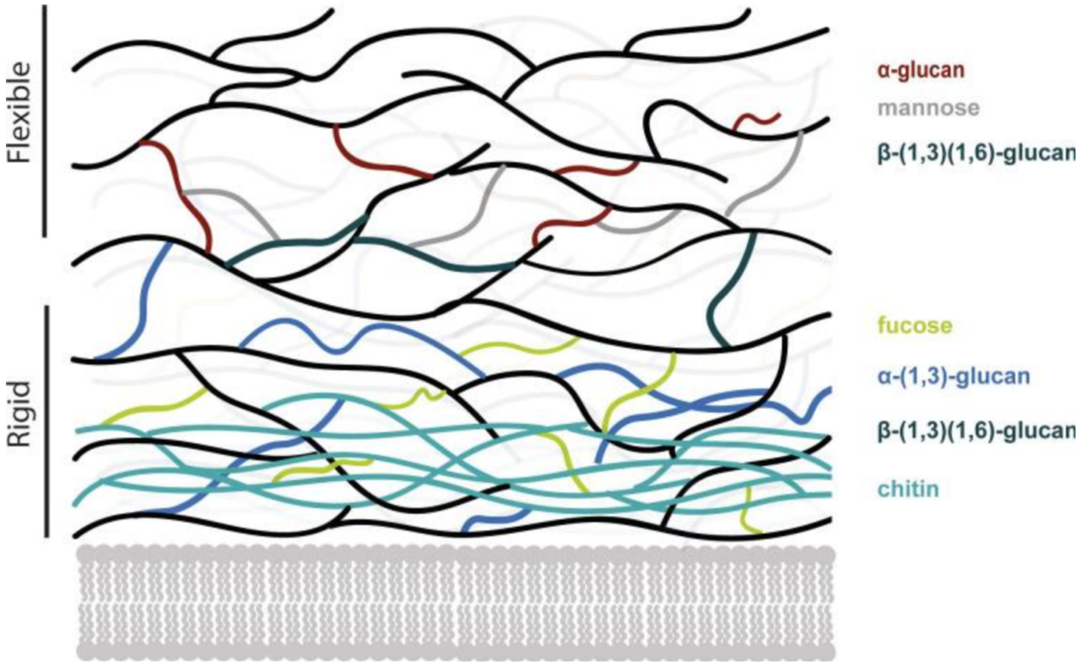

Figure 3. Model of the S. commune cell wall structure focusing on sugar composition. Taken from Appels et al. (2019) (ref. (Appels et al., 2019)).

2.2 Factors determining composite architecture

Mycelium bio bricks have to meet certain standards to be used for particular applications. The bio bricks need for instance a consistent morphology, density, strength, water-uptake capability and flexibility. This can be achieved by varying the substrate, the fungi used, environmental growth conditions and processing techniques (Appels et al., 2018, 2019; Jones et al., 2017; Xing et al., 2018).

2.2.1 Fungi species

Mycelium material characteristics can be affected by a single gene (Appels et al., 2018), illustrating that mycelium material properties can vary greatly if fungi differing in many more genes are used. The different properties can result from different colonization speeds and different polymer breakdown profiles (Haneef et al., 2017; Jones et al., 2017; Xing et al., 2018) but can also be impacted by the interaction of the hyphae with the substrate. A higher growth speed will bind the substrate particles more rapidly. However, to high colonization of the substrate may also negatively impact the properties, for instance by reducing the fiber strength of the substrates (Xing et al., 2018). So far, various fungi have been used to grow mycelium composites such as *Pleurotus ostreatus* (*P. ostreatus*), and *Ganoderma lucidum* (*G. lucidum*) (Antinori et al., 2020; Appels et al., 2019; Haneef et al., 2017; Jones et al., 2017; Joshi et al., 2020). ….

The amount of water taken up by the fungal bio brick will strongly impact the application performance on the one hand, and the degradation on the other hand. The more water is taken up by the material, the easier it will be broken down by microbes and the higher the chance that the material will have changed properties such as thickness due to swelling (Appels et al., 2019). For instance, research by Appels et al. (2019) experimented with materials resulting from *T. multicolor* and *P. ostreatus* grown on different substrates and treated with different pressing methods: *T. multicolor* on sawdust (TBN) and straw with (TRH) or without (TRN) heat pressing and growth of *P. ostreatus* on cotton with heat pressing (PCH), cold pressing (PCC) and without pressing (PCN) and on straw with heat pressing (PRH), cold pressing (PRC) and without pressing (PRN) (Appels et al., 2019). All materials increased in weight after placing them on top of water. TRN and PCN demonstrated the highest water uptake, whereas TBN showed the lowest. This can be explained by the fact that the it forms a water repellent fungal skin under these conditions. Therefore, it was shown that there was no relation between the type of fungus, substrate, or pressing conditions used and water absorption. (Appels et al., 2019). Research by López Nava et al. (2016) showed that other *Pleurotus*-based mycelium materials grown on a substrate consisting of grain fibres absorbed up to 278% water over a maximum of 24 hours. Mycelium composites based on cotton from an undocumented fungus absorbed 198% of water after being immersed for 168 hours (Appels et al., 2019; López Nava et al., 2016).

2.2.2 Feeding substrates

Filamentous fungi are capable to grow on low quality lignocellulolytic waste streams like sawdust and straw that cannot be used to feed animals (Appels et al., 2019; Haneef et al., 2017; Xing et al., 2018). The main component of lignocellulose is cellulose, which is a polysaccharide. It is the most abundant organic polymer on earth and functions as a structural component in the cell wall of plants. These polymers have to be broken down into smaller monomers and oligomers, which can be taken up to serve as nutrients. To do so, hyphae penetrate the substrate by secreting enzymes and applying physical pressure (Haneef et al., 2017; Jones et al., 2017; Reid & Webster, 2007). The morphology of the substrate (fibers versus dust; and long fibers vs short fibers) will strongly impact the bio brick properties. Also, the composition of the substrate has great impact (Appels et al., 2019; Jones et al., 2017). Depending on the right feeding substrates creates the feasibility to adjust mycelium materials to fit their use in different applications (Antinori et al., 2020; Haneef et al., 2017; Manan et al., 2021). By suitably selecting the feeding substrate, the morphology, growth rate, hydrodynamic, chemical and mechanical properties of the mycelium materials can be altered. (Antinori et al., 2020; Appels et al., 2019; Haneef et al., 2017; Manan et al., 2021). For example, a study by Haneef et al. (2017) grew mycelium materials for which two types of fungi, *P. ostreatus* and *G. lucidum*, were used. The substrates chosen in this research were pure cellulose and cellulose-potato dextrose broth (PDB). The reasons these substrates were chosen, are because cellulose is the most abundant polymer on this planet, and because PDB is known to contain a lot of simple sugars which means it is easy to digest for mycelium. Therefore, PDB is the most common medium promoting mycelial growth (Antinori et al., 2020; Haneef et al., 2017). Besides PDB, there are other commonly used substrates. Examples are agricultural waste streams, saw dust, hay, sugar cane, straw, wood pulp, millet grain, wheat bran, natural fibers and mixtures of these substates. Research showed that it is even possible to use banana fibers, which is a waste product, infused with resin made from banana sap as a substrate (Amstislavski et al., 2017; Islam et al., 2018; Paul et al., 2015). In this research by Haneef et al. it is shown that the ultimate fibrous constructions of the mycelial materials demonstrated diverse relative concentrations in polysaccharides, lipids, proteins and chitin (Haneef et al., 2017). These different concentrations are expressed as modifications in the morphology and mechanical properties of the mycelium. For instance, it has been shown that materials grown on cellulose substrates consist of higher concentrations of chitin and showed higher scores on Young's modulus (the modulus of elasticity in tension or compression)[1] (Antinori et al., 2020; Haneef et al., 2017). The lower the score on Young's modulus, the more elastic a material is, the higher the score, the stiffer the material is (Heuberger et al., 1995). Different fungi can respond differently to (changes in) feeding substrates. When comparing *G. lucidum* to *P. ostreatus*, both grown on cellulose, mycelium material from *G. lucidum* is more elastic than mycelium material from *P. ostreatus*, which is stiffer in this case. Nevertheless, both materials become more elastic when dextrose is added to the cellulose-based feeding substrate (Antinori et al., 2020; Appels et al., 2019; Haneef et al., 2017). Significant changes to the mycelium material properties can be made even by making small changes to the structure of a general fungal growth medium (Antinori et al., 2020).

2.2.3 Environmental factors

Mechanical properties of mycelium materials can be influenced by manipulating the environmental growth factors (Appels et al., 2018). Examples of such environmental growth factors are temperature, light, pH, water potential and nitrogen and carbon sources (Appels et al., 2018, 2019; Domingues et al., 2016; Fu et al., 2013; Haneef et al., 2017). Depending on the species of interest, there are optimal growth conditions. However, by altering certain environmental growth factors, properties like morphology, density, radial growth, Young's modulus (elasticity or elongation), and strength can be adjusted (Appels et al., 2018, 2019; Fu et al., 2013; Haneef et al., 2017; Zhao et al., 2010). For instance, Fu et al. (2013) examined the effects of various environmental factors on mycelial growth, such as how increasing temperature affects radial growth of two isolates of *Villosiclava virens* (*V. virens*), namely SC09 and SC32. *V. virens* causes rice false smut, which is a fungal disease that is found worldwide (Fu et al., 2013). As can be seen below in figure 3 (obtained from Fu et al., (2013)), both isolates responded very similarly to temperature in terms of radial growth (figure 4). Active mycelial growth took place in temperatures between 12 and 32 degrees Celsius. The inclining trend shows that the radial growth rate of both isolate SC09 and SC32 increased with the increasing temperature up to 28 or 30 degrees Celsius. This is where the optimal growth rate lies. As the temperature increased further, the mycelial growth decreased relatively rapidly and was arrested at 34 degrees Celsius. After this event, the isolates did not resume growth, despite the fact that they were incubated at the optimal temperature of 28 degrees Celsius for another 10 days. Therefore, it was assumed that the fungi had died (Fu et al., 2013). This data shows that temperature is a critical factor in mycelial growth.

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[1] Young's modulus is expressed in Pa, which is a unit of pressure (Newton per square meter). The lower the score on Young's modulus, the more elastic a material is, the higher the score, the stiffer the material is (Heuberger et al., 1995).

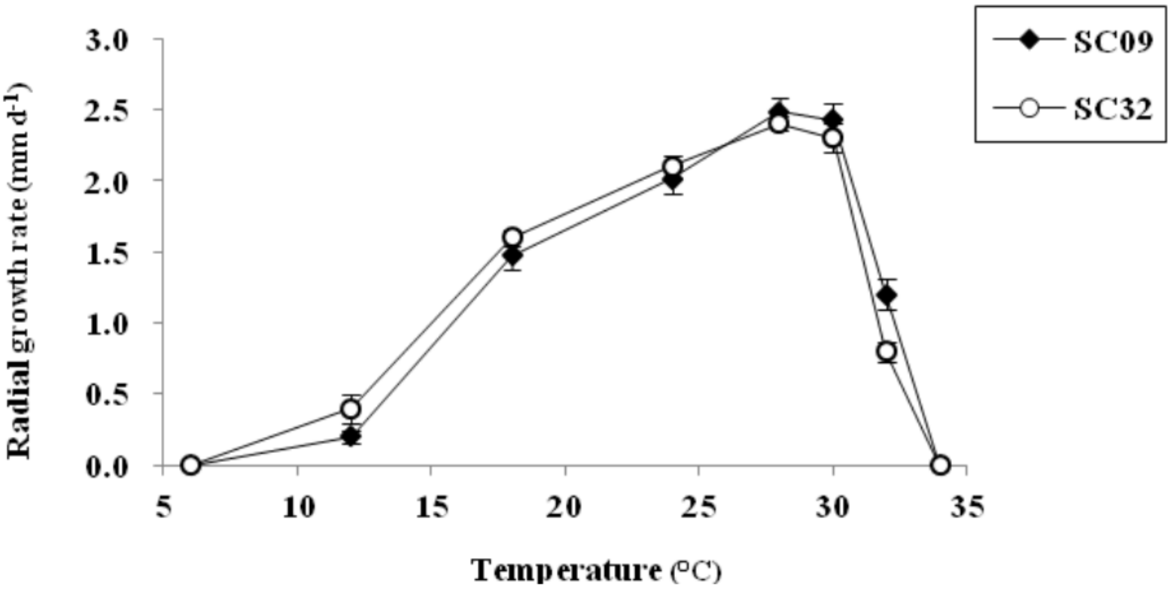

Figure 4. Effect of temperature on the radial mycelial growth rate (mm d^{-1}) of two isolates (SC09 and SC32) of *V. virens* on potato sucrose agar. The values are the means of pooled data of two experimental replicates (six repeat plates for each isolate at each temperature). Bars = standard errors. (Adapted from Fu et al. (2013)).

2.2.4 Pressing conditions

Besides manipulating mycelial composites during growth by using certain species, substrates and environmental factors, mycelium materials can also be manipulated after growth. Applying heat or cold pressing is a way to adequately improve structural features of mycelium materials (Appels et al., 2019; Liu et al., 2019; Manan et al., 2021). Generally, by pressing a material its density is increased and its porosity is reduced, which causes mycelial composites to become a more cork-like material, compared to a foam-like material when it is not pressed (Adamatzky et al., 2022; Appels et al., 2019; Manan et al., 2021; Thoemen & Humphrey, 2005). Figure 5, retrieved from Appels et al. (2019) shows a material chart of the different composite materials after applying different pressing conditions and the impact on their tensile strength, flexibility and density. Pressing also aids in horizontal rearrangement of fibers while reducing their thickness. This results in more contact between the fibers where they overlap (Thoemen & Humphrey, 2005). Heat-pressing in particular plays a vital role in enhancing tensile strength and modulus of the mycelial composites, compared to cold-pressing or no pressing at all (Adamatzky et al., 2022; Appels et al., 2019). Research conducted by Adamatzky et al. (2022) presented that however tensile properties can change depending on the feeding substrate, the experiments in this particular research resulted in a tensile strength that was averagely six times higher when heat-pressed compared to cold-pressed and non-pressed materials (Adamatzky et al., 2022).

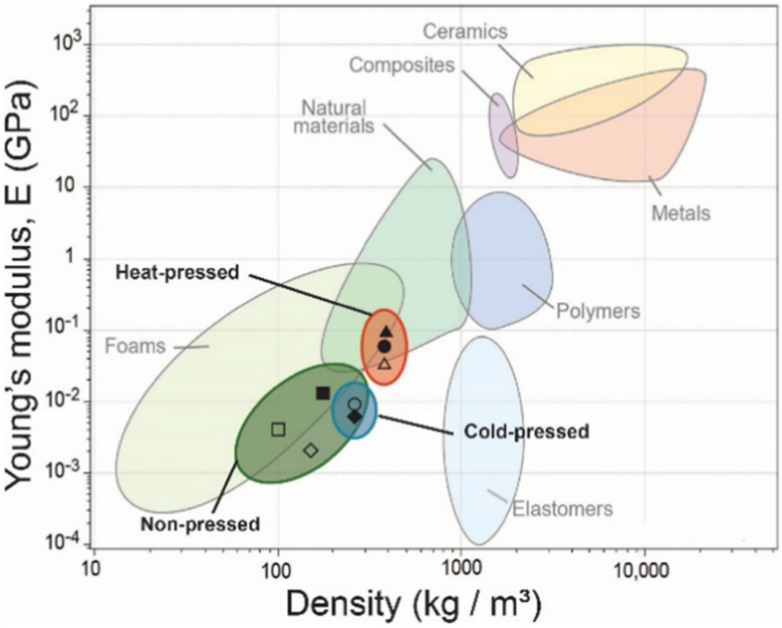

Figure 5. Material chart of different composite materials after applying different pressing conditions and the impact on their tensile strength, flexibility and density. Retrieved from Appels et al. (2019).

3. Coating materials

3.1 Why are coatings necessary?

Because mycelium-based composites are bio-composites that have biodegradable characteristics and therefore susceptible to (bio)degradation and decay (Brabcová et al., 2016; Rafiee et al., 2021; Vandelook et al., 2021), factors like microbial growth, insects feeding on the material and weathering conditions could negatively impact the quality of the materials (Brabcová et al., 2016; Chan et al., 2021; Elsacker et al., 2020). Therefore, protective coatings are necessary to prevent the mycelium materials from degrading (Elsacker et al., 2020; Schaak & Lucht, 2016). Another factor that could come into play as to why protective coatings are necessary is smell, as mycelium materials could emit an odor that could be experienced as unpleasant (Parisi et al., 2016; Vasquez & Vega, 2019). Applying a protective layer would inhibit the dispersion of unwanted odors.

3.2 Coating materials

As the aim of using mycelium-based composites is to increase circularity and reduce environmental impact, the coatings used on these materials should also fit the narrative of sustainable protection. Considering the fact that the current day coating industries are facing ecological as well as economic issues using and producing their conventional materials, such as petroleum-based polymers and other forms of chemicals and synthetic polymers, the need for a paradigm shift to bio-based, sustainable approach is high (Balgude & Sabnis, 2014; Paraskar et al., 2021; Thombare et al., 2022). There are various natural and sustainable materials available that have the potential to be applied to mycelium composite materials as coating and therefore protect them from decay.

3.2.1 Vegetable oils

Vegetable oil-based coatings are a great alternative to conventional petroleum-derived fuel-based polymeric materials. Not only is it a non-depletable raw material and therefore renewable source, other important requirements to create a viable, sustainable coating are also covered. For example, vegetable oils are readily and easily available. Moreover, vegetable oils are biodegradable, non-toxic to both humans and the environment, have a low viscosity and are low-cost (Alam et al., 2014; Samyn et al., n.d.; Thakur et al., 2019). Research has shown that because of their exceptional chemical structure vegetable oils are extremely versatile. By sustaining different chemical transformations, they can produce polymeric materials of low molecular weight which can be used in a variety of applications, especially as a main ingredient in paintings and coatings (Alam et al., 2014; Lligadas et al., 2013; Paraskar et al., 2021; Thakur et al., 2019).

Oil-based coatings can be derived from oil from different plant species, such as linseed, soybean, coconut, palm, rapeseed, corn, cotton and castor. Depending on which oil and chemically altering process is applied, different polymeric materials are produced. Some of the commonly produced polymeric coating materials are polyesteramides (PEA), which can be derived from linseed or coconut oil for example, polyurethanes (PU), which can be derived from oils such as soybean oil and rapeseed oil, and epoxies (Alam et al., 2014; Lligadas et al., 2013; Stemmelen et al., 2015). Many oils have been successfully epoxidized in past research, among which are linseed oil, soybean oil, rapeseed oil and maize oils. PEA has an advantage when it comes to resistance to chemicals, water vapor resistance and speed of drying. However, 50% of PEA is non-biodegradable, which could be considered an unfavorable characteristic (Alam et al., 2014; Mahapatra & Karak, 2004). PU also has a good set of features like elasticity, hardness, sound storage stability (up to 6 months) and mechanical resistance (Alam et al., 2014; Datta & Głowińska, 2012).

Figure 6. Different plant seeds that are commonly used to make vegetable oils from. In the pictures are depicted: A) linseeds, B) soybeans, C) rapeseeds, D) cottonseeds.

3.2.2 Xylho biofinish

Xylho biofinish is a method of protective wood coating, especially applicable to and most effective on wood that is used in outdoor applications. It is entirely eco-friendly, circular and based on natural and local resources. The principle of xylho coating rests on creating a natural protective biofilm based on linseed oil and functional micro-organisms. Most research about biofilms in construction in the past has been focused on the prevention of biofilms, as discoloring biofilms are usually considered to be negative (van Nieuwenhuijzen et al., 2018; Williams & Feist, 1999). For example, microbial growth on biofilms are commonly associated with health hazards due to mycotoxins (Görs et al., 2007), possible biodeterioration and degradation of aesthetics (Gorbushina et al., 2004; Kemmling et al., 2004). However, biofilms are also known to have positive functional characteristics when it comes to using them in construction, of which xylho coating provides such examples.

With xylho coating, wood is impregnated with linseed oil, after which the naturally occurring and harmless fungus *Aureobasidium pullulans* is grown on it. This results in a functional, living, water-repellent layer (figure 7) (M. F. Sailer, 2022). Not only does it protect against weathering, it also protects against UV-light and degradation caused by other microbes. (Michael F. Sailer et al., 2010). Moreover, this form of coating has several advantages over conventional wood protection. Firstly, one of the major advantages is the fact that it has the capability to heal itself if damage occurs. The biofilm is based on living cells, and the wood it is grown on functions as a nutrition reservoir. Under the right circumstances, oil secretion is triggered and the damages will be repaired by fungal growth. This self-healing principle is displayed in figure 8.

Figure 7. Profile of linseed impregnated pine wood finished with the *A. pullulans* protective fungus layer. Retrieved from Xylho Biofinish, 2022.

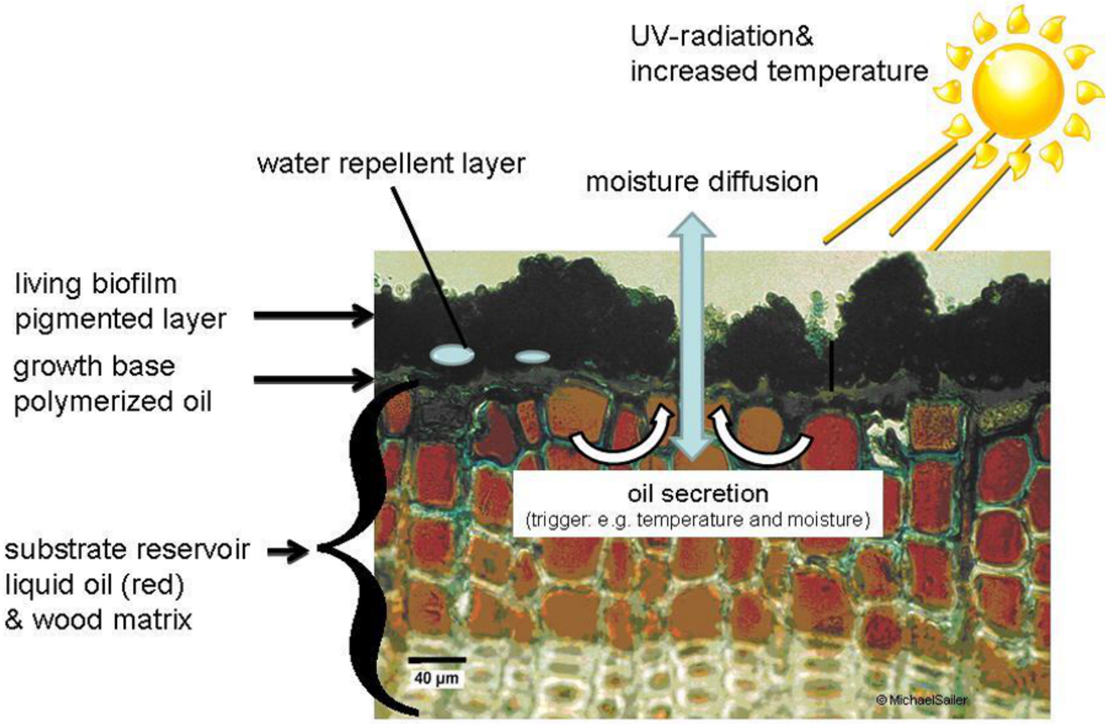

Figure 8. Self-healing principle of the biofilm (black) demonstrated on pine wood treated with linseed oil (red). Retrieved from Xylho Biofinish, 2022.

Another huge advantage the xylho biofilm coating has over conventional coatings, is that the fungal colonies constructing the biofilm move along with the wood as soon as it swells or shrinks, whereas other coatings are known to frequently crack (M. F. Sailer, 2022; Michael F. Sailer et al., 2010). Where the surface of conventional coatings is completely sealed off, the biofilm coating is not. This is why it can move with the wood without damaging the biofilm. These advantages over conventional coatings is what makes this method of coating extremely durable and sustainable.

3.2.3 Shellac

Lac is a natural resin that originates and is obtained from lac insects. These insects settle on the fragile shoots of particular host trees, get nourishment from their sap and conclude their life cycle. During their life cycle, the female insects secrete a protective coating around their body which is of resinous character (figure 9). This is then harvested as a lac crop. (K. Sharma, 2016; Thombare et al., 2022). After being harvested, lac goes through a series of processing steps to produce its more refined versions, as is visualized in figure 10. Shellac is such a physically polished version of lac resin. It has long been utilized in numerous industries, including surface coating, because of its excellent qualities, including the forming of films, water-resistance, adhering and bonding. Next to these properties, shellac is also a biodegradable material, non-toxic and environmentally safe (Chauhan et al., 2013; Musa et al., 2011; K. K. Sharma et al., 2020; Thombare et al., 2022; Yuan et al., 2021).

To get to the refined form of lac that is shellac, several processing steps need to be walked through (fig 10). Firstly, the twigs are trimmed from the lac host tree after which the lac encrustation is scraped off of them using tools like a knife or a sickle. Therefore, the product that

Figure 9. Lac growth on a host plant. A shows the insect settlement, B the intermediate stage and C the mature crop. Obtained from Thombare et al., 2022.

comes from this is called scrapedlac or sticklac and is depicted in figure 10b. Sticklac comprises between 30 and 40 percent impurities, which are eliminated during the first lac processing step, which contains five unit processes in itself, including crushing and washing (fig. 10) (K. K. Sharma et al., 2020; Thombare et al., 2022). This outcome of this step is seedlac (fig. 10d), which is a semi-purified product processed to create shellac with. One of three techniques can be used to accomplish this (K. K. Sharma et al., 2020; Thombare et al., 2022). The first method is by using heat. The steam heat used in this production process melts the seedlac. In a hydraulic press, the then molten lac is forced through a filter by applying hydraulic force. With the aid of a sheeting roller, this filtered lac is next stretched into long sheets, after which the sheets are broken up into tiny flakes known as machine-made shellac (Dhiraj Kumar & Shahid, 2020; Thombare et al., 2022). The second method is based on solvent extraction. Here, the seedlac is dissolved in a cold or hot solvent, oftentimes alcohol. The insoluble residue is put aside to settle before being filtered (Mandal & Sarkhel, 2014). Following the distillation of the solvents, a sheeting roller is used to stretch the leftover molten shellac. After amendments, the solvent can be used again. As can be seen in figure 10(e), the natural color of the lac resin and therefore the shellac looks somewhat

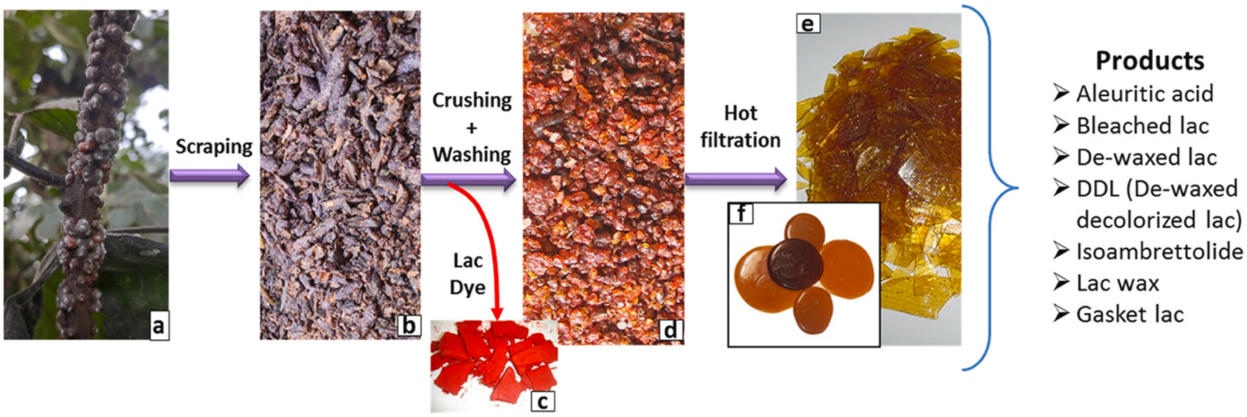

Figure 10. Processing of lac: (a) Lac on host plant, (b) Scraped lac, (c) Lac dye, (d) Seedlac, (e) Shellac and (f) Button lac and other products (value-added) obtained from lac. Retrieved from Thombare et al., 2022.

brown or yellow, caused by pigments secreted by the lac insects during their lives (K. K. Sharma, 2017). As this can be an undesired aspect, the alcoholic extract can be treated with an appropriate decolorizing agent if necessary. The third method is called the country process, also known as the "Bhatta process". It is a traditional method and is executed completely by manual labor, therefore it takes qualified people with a very specific skillset to do this (Brydson, 1999; Derry, 2012). A cloth bag of roughly 10 meters in length and 5 to 7,5 centimeters wide is used to put the seedlac in. Then, the filled bag gets warmed up in sections, in a charcoal fire oven (Derry, 2012). While one side of the bag is kept close to the oven, the other end is manually twisted repeatedly. As the heat causes the lac resin and its accompanying wax to melt, the twisting motions force it to be pushed through the cloth. Using a spatula, the squeezed out molten lac is then removed from the cloth's surface and combined with water to counteract thermal effects of the fused resin (Mandal & Sarkhel, 2014; Thombare et al., 2022). Once enough of the thoroughly mixed, molten lac resin is collected, it is spread out into a sheet and carefully stretched by hand to obtain a uniform thickness and shine. After cooling down, the sheet will be brittle and broken into tiny shellac flakes (Derry, 2012; Mandal & Sarkhel, 2014; Thombare et al., 2022).

Because of its excellent properties, shellac has been used in the coating industry for ages, for example as a varnish or sealant. The solvent is applied, and once it evaporates, it leaves a solid, hard film on the surface of the material it was applied to (Licchelli et al., 2013; Sen & Venugopalan, 1948). Moreover, halfway through the twentieth century shellac varnishes were developed that were airdrying and quick and easy to apply by brush or spray (Bhattacharya, 1947). Over the years through addition of certain elements, properties of shellac-based varnishes like water-, heat- and solvent resistance increased (Renfrew et al., 1954; Thombare et al., 2022).

As has been mentioned before, shellac is non-toxic, biodegradable and environmentally safe (Chauhan et al., 2013; Musa et al., 2011; Yuan et al., 2021). It is a fantastic choice as a coating agent due to its superb film-forming and binding qualities as well as its biocompatibility and easy applicability (Farag & Leopold, 2011) and would therefore be a possible contender as a bio-finish for mycelium construction material.

3.2.4 Nanocellulose

Because of their sustainable qualities and their usefulness in a wide range of industries, including composites, filtering, membranes, packaging, medical, industrial, construction, cosmetics, and foods, cellulose nanofibers and nanocrystals have been widely studied over the recent years (Abdul Khalil et al., 2016; Silva et al., 2020). Examples of cellulose-rich sources nanocellulose can be extracted from are banana, oil palm, cotton, wheat, bamboo, hemp, corn and rice, all of which are renewable sources (Abdul Khalil et al., 2014; Kalia et al., 2011). Aside from their highly beneficial properties concerning sustainability and biodegradability, nanocellulose-based films and coatings demonstrate outstanding resistance against oxygen, grease and mineral oils (Gicquel et al., 2017a; Koppolu et al., 2019; Shimizu et al., 2016). However, there are some disadvantages that are to be taken into account when looking into using nanocellulose-based films and coatings.

One of the major weaknesses of nanocellulose-based coatings, is that they are inappropriate for use in environments with high relative humidity (RH) due to their sensitivity to moisture (Koppolu et al., 2019; Spence et al., 2011). The majority of the barrier characteristics of nanocellulose deteriorate as the RH approaches 90% (Spence et al., 2011). Furthermore, the viscosity of most nanocellulose suspensions is very high (Gicquel et al., 2017b; Nazari et al., 2016).

Research by Nazari et al. (2016) and Kumar et al. (2017) shows that suspensions containing low solid content (typically below 5%) already yield stress (V. Kumar et al., 2017; Nazari et al., 2016). Additionally, nanocellulose suspensions are known to have difficulties adhering to certain substrates which poses issues concerning the processing speed (V. Kumar et al., 2017). Also, the mechanical processing of nanocellulose requires a lot of energy, which has so far made it difficult for them to enter a larger commercial market (Bharimalla et al., 2015).

Although nanocellulose shows great possibilities as a sustainable, environmentally friendly and biodegradable coating material, it also shows some unfavorable properties. These drawbacks could weaken the coating. Therefore, when applied onto mycelium materials could this negatively affect them leave them less protected. In order to improve these properties, more research is necessary.

4. Discussion

As stated by previous research, there is a high necessity to make the paradigm shift from the current way of production and consumption, based on disposal and depletion of non-renewable resources, to a sustainable and circular system, increasing the efficiency of resource use (Jones et al., 2017; Murray et al., 2017; Preston, 2012). As the production of synthetic materials depends heavily on non-renewable resources like petroleum, shifting to bio-based materials, especially fungal mycelium materials, contributes massively to the shift to a circular economy.

Research has shown it is possible to use mycelium materials in construction by creating mycelium composite bricks. In order for these bricks to be successful in construction, they need to meet certain requirements when it comes to their properties like a consistent morphology, density, and strength (Jones et al., 2017; Xing et al., 2018). Being able to tune the mycelial properties by adjusting the growth circumstances provides mycelium composites with a huge advantage. Adjusting the different growth factors makes it possible to create mycelium composites that hold the properties most favorable for their particular application (Appels et al., 2019). For example, feeding substrates impact mycelial properties. As mycelium can grow on low quality lignocellulolytic waste streams, this seems like a good way to increase circularity and use said readily available waste streams to grow mycelium composites on. However, particular waste streams that are available at that time might not give the mycelium composites the desired properties that another feeding substrate would. The quality and chemical composition of the feeding substrate is also of importance. Even slight changes to the feeding substrate can cause significant changes to the morphology and mechanical properties of the mycelium (Antinori et al., 2020; Appels et al., 2019; Haneef et al., 2017).

Aside from manipulating mycelial growth, there is also the possibility to alter the characteristics of mycelium materials after growing them. Research by Appels and colleagues (2018) has shown that applying different pressing conditions reveals a wide range of variations in density, tensile strength, material flexibility, and water absorption, opening the door to a variety of mycelium-based composite materials. Important findings were that heat pressing produced materials with qualities similar to those of wood and cork (Appels et al., 2019), which can be of great use in the area of construction. An increasing number of artists and designers are exploring the idea of building with mycelium, like the structures shown in figure 1. The idea to use mycelium materials for temporary buildings for temporary activities and events is especially popular. For example, in Kerala (India) a pavilion was built using mycelium materials to demonstrate this (fig. 11) (Frearson, 2017). Because the mycelium materials are easily biodegradable and can therefore be put back into the natural system after use, it is ideal for temporary events (Morby, 2017). However, more research on creating long lasting mycelium constructions is needed.

Figure 11. The "Shell Mycelium Installation" by Asif Rahman of the Indian studio Beetles 3.3, and Giombattista Arredia and Mohamad Yassin of an Italian architecture studio. The pavilion was meant for temporary use.

Protective coatings are necessary to protect mycelial bricks and structures from decay (Elsacker et al., 2020; Schaak & Lucht, 2016). Not only is this important for use in temporary structures, but particularly for potential durable use. As the production of synthetic coating materials relies heavily on depletable resources like petroleum, there is a high demand for bio-based alternatives (Balgude & Sabnis, 2014; Paraskar et al., 2021; Thombare et al., 2022). However, when it comes to their properties, the bio-based alternatives usually have some disadvantages compared to their synthetic counterparts. Therefore, more research on bio-based coatings applied to and on mycelium materials is necessary. Even though they might have some drawbacks compared to synthetic polymers, environmentally they propose huge advantages as they are derived from natural and renewable resources.

Bio-polymers derived from vegetable oils like polyesteramides (PEA) and polyurethanes (PU) are great possibilities as bio-based finishes for mycelium materials (Alam et al., 2014; Lligadas et al., 2013; Stemmelen et al., 2015). PEA has an advantage over PU when it comes to resistance to chemicals, moisture resistance and speed of drying. However, 50% of PEA is non-biodegradable, which could be considered an unfavorable characteristic, looking at sustainability and environmental impact (Alam et al., 2014; Mahapatra & Karak, 2004). PU shows to perform well in terms of elasticity, hardness, storage stability and mechanical resistance (Alam et al., 2014; Datta & Głowińska, 2012). Some problems concerning the production of oil-based polymers are reduced yield due to formation of side products, extended curing times and drying time (Alam et al., 2014). Altogether, they compete well with their synthetic counterparts. More research on how best to apply oil-based coatings to mycelium materials (e.g., brushing, impregnating) and their performance on those particular materials needs to be done.

Vegetable oils are products that are widely used and therefore also part of waste streams. This does not only include waste cooking oil, but also waste on an industrial scale. To illustrate, corn is the major component in the bioethanol industry in the United States of America (Deepak Kumar & Singh, 2018). The Renewable Fuels Association reported in 2017 that close to 3575 million pounds of corn oil was produced by the bioethanol industry as a byproduct in the USA alone (RFA, 2017; Thakur et al., 2019). As it is a waste product produced in such high amounts, there is a necessity to find an application that would add value to this downstream corn oil (DCO). Therefore, this DCO would be a possible starting material to produce vegetable-oil based coatings with (Thakur et al., 2019). As this adds value to a waste product that can then be reapplied, circularity of the process would be increased.

Whereas past research mostly looked to prevent biofilms from growing on construction materials, xylho coating is a way to use this naturally occurring biofilm to benefit from it. It has several advantages over conventional coating methods (M. F. Sailer, 2022; van Nieuwenhuijzen et al., 2018). It is completely based on locally sourced, renewable resources, sustainable, and environmentally friendly. One of the most significant benefits of xylho coating, is the fact that is way less susceptible to damaging due to swelling and shrinking of the wood, as the living biofilm moves along with it where conventional coatings are likely to tear. This is highly beneficial in (quickly) changing weather conditions. Applying xylho bio-finish to mycelium materials would mean that they would have to be impregnated with linseed oil as a nutrition source for the fungus creating the biofilm. As long as there is oil, the coating layer will stay intact. For temporary structures, this would pose no problems. However, for potential use of mycelium bricks in long-term structures, this would mean that they would have to be reimpregnated every now and again to maintain the fungal biofilm. Future research on how exactly these type of living biofilms would work on mycelium composites would be necessary. Another possible drawback concerning this type of coating is the fact that many people still have negative associations with fungi and think of them as health hazards and not aesthetically pleasing (Görs et al., 2007; Nalewicki, 2017; Michael F. Sailer et al., 2010) and would therefore possibly not want it as a living surface coating. More education regarding fungi would be necessary to change these general ideas.

Shellac has long been utilized in numerous industries, including surface coating, because of its excellent qualities, including the forming of films, water-resistance, adhering and bonding. Next to these properties, shellac is also a biodegradable material, non-toxic and environmentally safe (Chauhan et al., 2013; Musa et al., 2011; K. K. Sharma et al., 2020; Thombare et al., 2022; Yuan et al., 2021). However, the production process is relatively extensive and happens mostly in Asia, as this is where the lac insects and host trees naturally occur (Thombare et al., 2022). Focusing on western Europe as one of the main importers of lac and the accompanying intercontinental transportation, this could be considered less sustainable. Furthermore, the lac insects need to complete their life cycle before being harvested as a lac crop (K. K. Sharma, 2015; Thombare et al., 2022). Depending on the host tree and strain of lac insects, their life cycle can take 3 to 8 months to complete (K. K. Sharma, 2015). Adding this to the relatively extensive production process after harvesting, this is a quite time-consuming method. Aside from that, with its good properties, scoring high on sustainability and renewability scale and being easy to apply, shellac is a good contender as a bio-based coating for mycelium bricks.

Nanocellulose-based coatings provide great potential as a bio-based coating. However, there are some weaknesses to take into account, like their sensitivity to moisture and high viscosity (Gicquel et al., 2017a; Koppolu et al., 2019; Nazari et al., 2016; Spence et al., 2011). A possibility to counteract these drawbacks, is to create a multilayer barrier coating combining nanocellulose with polylactic acid (PLA) (Koppolu et al., 2019). For example, where nanocellulose shows low tolerance to water vapor, but high tolerance to oxygen, PLA has a high tolerance to water vapor, but a low tolerance to oxygen (Koppolu et al., 2019). Research by Koppolu and colleagues (2019) explores the possibility of combining these two into multilayer barriers. For instance, it shows that in comparison to nanocellulose alone, the grease barrier for nanocellulose + PLA coatings increased 5-fold, and comparing to PLA alone, it increased 2-fold. It also proved that the oxygen transmission rate was reduced by 98 percent, and the vapor transmission rate was reduced by 99 percent with the multilayer coating compared to the PLA coating alone (Koppolu et al., 2019). Hence, combining these two bio-based coatings into one multilayered coating could strengthen its qualities and make for a more resistant coating material.

It is clear that bio-based polymers as coating materials show great potential in the field. Using waste streams and other renewable sources to derive them from, huge strides are made in the paradigm shift towards a more sustainable, circular economy. However, as little is known about the performances of these coating materials on mycelium-based materials and how to best apply them, more research still needs to be done.

Using mycelium materials for temporary constructions is a great first step in normalizing these materials among the public. To get rid of the stigma fungi carry as hazardous, more education on the subject, also in context with the importance and necessity to shift to a circular economy, is necessary.

5. Conclusion

This research was carried out to gain insight in the possibility of using bio-based polymers as coating materials to protect mycelium composites from decay, as the idea to use them in construction is being explored. Mycelium composites can already be manipulated into having the desired properties during their growth process, which is advantageous. Various artists and designers have already used mycelium bricks in structures for temporary events, but protection against decay is especially important for structures that need to last longer. Different bio-polymers were looked into, considering their production process, properties and potential drawbacks. Vegetable oil-based bio-polymers have been widely researched and have desirable properties such as great resistance to chemicals and moisture. Xylho coating also shows great possibility as it is very resilient to environmental changes. However, as living biofilms are still often thought of negatively, this might pose some issues as for using it in common places. Shellac has been used in the coating industry for a long time. Aside from the production process being relatively extensive, it also only takes place in Asia, making intercontinental transportation a must. This could be considered a drawback within the sustainability scope. Nanocellulose coatings would work best when combined with polylactic acid to a multilayer barrier coating, as their performance then significantly improves. Altogether, currently still little is known about the performance and effectiveness of these bio-polymers in coating applications on mycelium materials. Therefore, more research on this topic is needed to take the paradigm shift to a circular economy to the next level.

6. References

Abdul Khalil, H. P. S., Davoudpour, Y., Islam, M. N., Mustapha, A., Sudesh, K., Dungani, R., & Jawaid, M. (2014). Production and modification of nanofibrillated cellulose using various mechanical processes: A review. *Carbohydrate Polymers*, *99*, 649–665.

Abdul Khalil, H. P. S., Davoudpour, Y., Saurabh, C. K., Hossain, M. S., Adnan, A. S., Dungani, R., Paridah, M. T., Mohamed, Z. I. S., Fazita, M. R. N., Syakir, M. I., & Haafiz, M. K. M. (2016). A review on nanocellulosic fibres as new material for sustainable packaging: Process and applications. *Renewable and Sustainable Energy Reviews*, *64*, 823–836.

Adamatzky, A., Wösten, H. A. B., Ayres, P., Elsacker, E., De Laet, L., & Peeters, E. (2022). Functional Grading of Mycelium Materials with Inorganic Particles: The Effect of Nanoclay on the Biological, Chemical and Mechanical Properties. *Biomimetics 2022, Vol. 7, Page 57*, *7*(2), 57.

Alam, M., Akram, D., Sharmin, E., Zafar, F., & Ahmad, S. (2014). Vegetable oil based eco-friendly coating materials: A review article. *Arabian Journal of Chemistry*, *7*(4), 469–479.

Amstislavski, P., White, M., Still, B., Yang, Z. (Joey), & Zhang, F. (2017). Physical and Mechanical Properties of Fungal Mycelium-Based Biofoam. *Journal of Materials in Civil Engineering*.

Antinori, M. E., Ceseracciu, L., Mancini, G., Heredia-Guerrero, J. A., & Athanassiou, A. (2020). Fine-Tuning of Physicochemical Properties and Growth Dynamics of Mycelium-Based Materials. *ACS Applied Bio Materials*, *3*(2), 1044–1051.

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

Appels, F. V. W., Dijksterhuis, J., Lukasiewicz, C. E., Jansen, K. M. B., Wösten, H. A. B., & Krijgsheld, P. (2018). *Hydrophobin gene deletion and environmental growth conditions impact mechanical properties of mycelium by affecting the density of the material*. *August 2017*, 1–7.

Averous, L., Moro, L., Dole, P., & Fringant, C. (2000). Properties of thermoplastic blends: Starch-polycaprolactone. *Polymer*.

Babu, R. P., O'Connor, K., & Seeram, R. (2013). Current progress on bio-based polymers and their future trends. *Progress in Biomaterials*.

Balgude, D., & Sabnis, A. S. (2014). *CNSL: an environment friendly alternative for the modern coating industry*.

Bharimalla, A. K., Deshmukh, S. P., Patil, P. G., & Vigneshwaran, N. (2015). Energy Efficient Manufacturing of Nanocellulose by Chemo- and Bio-Mechanical Processes: A Review. *World Journal of Nano Science and Engineering*, *05*(04), 204–212.

Bhattacharya, G. N. (1947). *On the suitability of the dielectric constant method for the determination of moisture in lac*.

Bonfante, P., & Genre, A. (2010). Mechanisms underlying beneficial plant - Fungus interactions in mycorrhizal symbiosis. In *Nature Communications*.

Boucher, O., Friedlingstein, P., Collins, B., & Shine, K. P. (2009). The indirect global warming potential and global temperature change potential due to methane oxidation. *Environmental Research Letters*.

Brabcová, V., Nováková, M., Davidová, A., & Baldrian, P. (2016). Dead fungal mycelium in forest soil represents a decomposition hotspot and a habitat for a specific microbial community. *New Phytologist*, *210*(4), 1369–1381.

Brydson, J. A. (1999). Plastics Materials. *Elsevier*.

Cerimi, K., Akkaya, K. C., Pohl, C., Schmidt, B., & Neubauer, P. (2019). Fungi as source for new bio-based materials: a patent review. *Fungal Biology and Biotechnology 2019 6:1*, *6*(1), 1–10.

Chan, X. Y., Saeidi, N., Javadian, A., Hebel, D. E., & Gupta, M. (2021). Mechanical properties of dense mycelium-bound composites under accelerated tropical weathering conditions. *Scientific Reports 2021 11:1*, *11*(1), 1–10.

Chauhan, O. P., Nanjappa, C., Ashok, N., Ravi, N., Roopa, N., & Raju, P. S. (2013). *Shellac and Aloe vera gel based surface coating for shelf life extension of tomatoes*.

Dahiya, S., Katakojwala, R., Ramakrishna, S., & Mohan, S. V. (2020). Biobased Products and Life Cycle Assessment in the Context of Circular Economy and Sustainability. *Materials Circular Economy 2020 2:1*, *2*(1), 1–28.

Datta, J., & Głowińska, E. (2012). Chemical modifications of natural oils and examples of their usage for polyurethane synthesis: *Http://Dx.Doi.Org/10.1177/0095244312459282*, *46*(1), 33–42.

Derry, J. (2012). Investigating shellac: documenting the process, defining the product. A study on the processing methods of shellac, and the analysis of selected physical and chemical characteristics. *The Institute of Archeology, Conservation and History, Faculty of Humanities, Master The*.

Domingues, M. V. P. F., de Moura, K. E., Salomão, D., Elias, L. M., & Patricio, F. R. A. (2016). Effect of temperature on mycelial growth of *Trichoderma, Sclerotinia minor* and *S. sclerotiorum,* as well as on mycoparasitism. *Summa Phytopathologica*, *42*(3), 222–227.

Dougoud, M., Corser, R., Simonen, K., & Meek, C. (2018). *Mycelium Infrastructures for Impermanent Futures Revitalization of an industrial site through the manufacturing and research of mycelium- based biocomposite materials*.

Ehren, H. L., Appels, F. V. W., Houben, K., Renault, M. A. M., Wösten, H. A. B., & Baldus, M. (2020). Characterization of the cell wall of a mushroom forming fungus at atomic resolution using solid-state NMR spectroscopy. *The Cell Surface*, *6*.

Elsacker, E., Vandelook, S., Van Wylick, A., Ruytinx, J., De Laet, L., & Peeters, E. (2020). A comprehensive framework for the production of mycelium-based lignocellulosic composites. *Science of The Total Environment*, *725*, 138431.

Farag, Y., & Leopold, C. S. (2011). Development of shellac-coated sustained release pellet formulations. *European Journal of Pharmaceutical Sciences*, *42*(4), 400–405.

Frearson, A. (2017). *Fungus used to build arching pavilion in Kerala*. https://www.dezeen.com/2017/08/26/shell-mycelium-fungus-pavilion-beetles-3-3-yassin-arredia-design-kerala-india/

Fu, R., Yin, C., Liu, Y., Ding, L., Zhu, J., Zheng, A., & Li, P. (2013). The influence of nutrient and environmental factors on mycelium growth and conidium of false smut Villosiclava virens. *African Journal of Microbiology Research*, *7*(9), 825–833.

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy : the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11–32.

Gicquel, E., Martin, C., Garrido Yanez, J., & Bras, J. (2017a). Cellulose nanocrystals as new bio-based coating layer for improving fiber-based mechanical and barrier properties. *Journal of Materials Science*, *52*(6), 3048–3061.

Gicquel, E., Martin, C., Garrido Yanez, J., & Bras, J. (2017b). Cellulose nanocrystals as new bio-based coating layer for improving fiber-based mechanical and barrier properties. *Journal of Materials Science*, *52*(6), 3048–3061.

Gorbushina, A. A., Heyrman, J., Dornieden, T., Gonzalez-Delvalle, M., Krumbein, W. E., Laiz, L., Petersen, K., Saiz-Jimenez, C., & Swings, J. (2004). Bacterial and fungal diversity and biodeterioration problems in mural painting environments of St. Martins church (Greene–Kreiensen, Germany). *International Biodeterioration & Biodegradation*, *53*(1), 13–24.

Görs, S., Schumann, R., Häubner, N., & Karsten, U. (2007). Fungal and algal biomass in biofilms on artificial surfaces quantified by ergosterol and chlorophyll a as biomarkers. *International Biodeterioration and Biodegradation*, *60*(1), 50–59.

Haneef, M., Ceseracciu, L., Canale, C., Bayer, I. S., Heredia-Guerrero, J. A., & Athanassiou, A. (2017). Advanced Materials from Fungal Mycelium: Fabrication and Tuning of Physical Properties. *Scientific Reports*, *7*(December 2016), 1–11.

Heuberger, M., Dietler, G., & Schlapbach, L. (1995). Mapping the local Young's modulus by analysis of the elastic deformations occurring in atomic force microscopy. *Nanotechnology*, *6*(1), 12.

Islam, M. R., Tudryn, G., Bucinell, R., Schadler, L., & Picu, R. C. (2017). Morphology and mechanics of fungal mycelium. *Scientific Reports*, *7*(1), 1–12.

Islam, M. R., Tudryn, G., Bucinell, R., Schadler, L., & Picu, R. C. (2018). Mechanical behavior of mycelium-based particulate composites. *Journal of Materials Science*, *53*(24), 16371–16382.

Jiang, L., Walczyk, D., Mooney, L., & Putney, S. (2016). *Manufacturing of Mycelium-Based Biocomposites*. *July*.

Jones, M., Huynh, T., Dekiwadia, C., Daver, F., & John, S. (2017). *Mycelium Composites : A Review of Engineering Characteristics and Growth Kinetics*. *11*(4).

Joshi, K., Meher, M. K., & Poluri, K. M. (2020). Fabrication and Characterization of Bioblocks from Agricultural Waste Using Fungal Mycelium for Renewable and Sustainable Applications. *ACS Applied Bio Materials*, *3*(4), 1884–1892.

Kalia, S., Dufresne, A., Cherian, B. M., Kaith, B. S., Avérous, L., Njuguna, J., & Nassiopoulos, E. (2011). Cellulose-based bio- and nanocomposites: A review. *International Journal of Polymer Science*, *2011*.

Kemmling, A., Kämper, M., Flies, C., Schieweck, O., & Hoppert, M. (2004). Biofilms and extracellular matrices on geomaterials. *Environmental Geology*, *46*(3–4), 429–435.

Koppolu, R., Lahti, J., Abitbol, T., Swerin, A., Kuusipalo, J., & Toivakka, M. (2019). *Continuous Processing of Nanocellulose and Polylactic Acid into Multilayer Barrier Coatings*.

Kumar, Deepak, & Singh, V. (2018). Bioethanol production from corn. *Corn: Chemistry and Technology, 3rd*

Edition, 615–631.

Kumar, Dhiraj, & Shahid, M. (2020). Natural materials and products from insects: Chemistry and applications. *Natural Materials and Products from Insects: Chemistry and Applications*, *May*, 1–1556.

Kumar, V., Koppolu, V. R., Bousfield, D., & Toivakka, M. (2017). *Substrate role in coating of microfibrillated cellulose suspensions*.

Licchelli, M., Malagodi, M., Somaini, M., Weththimuni, M., & Zanchi, C. (2013). Surface treatments of wood by chemically modified shellac. *Surface Engineering*, *29*(2), 121–127.

Liu, R., Long, L., Sheng, Y., Xu, J., Qiu, H., Li, X., Wang, Y., & Wu, H. (2019). Preparation of a kind of novel sustainable mycelium/cotton stalk composites and effects of pressing temperature on the properties. *Industrial Crops and Products*, *141*, 111732.

Lligadas, G., Ronda, J. C., Galià, M., & Cádiz, V. (2013). Renewable polymeric materials from vegetable oils: A perspective. *Materials Today*, *16*(9), 337–343.

López Nava, J. A., Méndez González, J., Ruelas Chacón, X., & Nájera Luna, J. A. (2016). Assessment of Edible Fungi and Films Bio-Based Material Simulating Expanded Polystyrene. *Http://Dx.Doi.Org/10.1080/10426914.2015.1070420*, *31*(8), 1085–1090.

Mahapatra, S. S., & Karak, N. (2004). Synthesis and characterization of polyesteramide resins from Nahar seed oil for surface coating applications. *Progress in Organic Coatings*, *51*(2), 103–108.

Manan, S., Ullah, M. W., Ul-Islam, M., Atta, O. M., & Yang, G. (2021). Synthesis and applications of fungal mycelium-based advanced functional materials. *Journal of Bioresources and Bioproducts*, *6*(1), 1–10.

Mandal, J., & Sarkhel, J. (2014). Analysis of Cost Effectiveness of Lac Processing in Purulia District. *Business Spectrum*, *4*(2), 35–44.

McGaw, J. (2018). Dark matter. *Architectural Theory Review*, *22*(1), 120–139.

Morby, A. (2017). *Structure grown from "mushroom sausages" shows potential for zero-waste architecture*.

Murray, A., Skene, K., Haynes, K., Murray, A., Skene, K., & Haynes, K. (2017). The Circular Economy : An Interdisciplinary Exploration of the Concept and Application in a Global Context. *Journal of Business Ethics*, *140*(3), 369–380.

Musa, T. N., Ulaiwi, W. S., & Al-Hajo, N. N. A. (2011). The effect of shellac as coating material on the internal quality of chicken eggs. *International Journal of Poultry Science*, *10*(1), 38–41.

Naeger, N. L., Stamets, P. E., Sheppard, W. S., Sumerlin, D., Carris, L. M., Moershel, H. M., Hopkins, B. K., Taylor, A. W., Lopez, D., Han, J. O., Evans, J. D., & Nally, R. (2018). Extracts of Polypore Mushroom Mycelia Reduce Viruses in Honey Bees. *Scientific Reports*, *8*(1), 1–6.

Nalewicki, J. (2017). Is Fungus the Material of the Future? *Smithsonian Magazine*.

Nazari, B., Kumar, V., Bousfield, D. W., & Toivakka, M. (2016). Rheology of cellulose nanofibers suspensions: Boundary driven flow. *Journal of Rheology*, *60*(6), 1151.

Ness, D., & Ness, D. (2010). *Sustainable urban infrastructure in China : Towards a Factor 10 improvement in resource productivity through integrated infrastructure systems Sustainable urban infrastructure in China : Towards a Factor 10 improvement in resource productivity through int*. *4509*.

Papagianni, M. (2004). Fungal morphology and metabolite production in submerged mycelial processes. *Biotechnology Advances*, *22*(3), 189–259.

Paraskar, P. M., Prabhudesai, M. S., Hatkar, V. M., & Kulkarni, R. D. (2021). Vegetable oil based polyurethane coatings – A sustainable approach: A review. *Progress in Organic Coatings*, *156*.

Parisi, S., Rognoli, V., & Ayala-Garcia, C. (2016). Designing materials experiences through passing of time - Material driven design method applied to mycelium-based composites. *Proceedings - D and E 2016: 10th International Conference on Design and Emotion - Celebration and Contemplation*, *March 2020*, 239–255.

Park, J. Y., & Chertow, M. R. (2014). Establishing and testing the " reuse potential " indicator for managing wastes as resources. *Journal of Environmental Management*, *137*, 45–53.

Paul, V., Kanny, K., & Redhi, G. G. (2015). Mechanical, thermal and morphological properties of a bio-based composite derived from banana plant source. *Composites Part A: Applied Science and Manufacturing*.

Peters, T. (2015). Sustaining the local: An alternative approach to sustainable design. *Architectural Design*, *85*(2), 136–141.

Posch, A. (2010). *Industrial Recycling Networks as Starting Points for Broader Sustainability-Oriented Cooperation? 14*(2).

Preston, F. (2012). *briefing paper A Global Redesign ? Shaping the Circular Economy*. *March*.

Rafiee, K., Schritt, H., Pleissner, D., Kaur, G., & Brar, S. K. (2021). Biodegradable green composites: It's never too late to mend. *Current Opinion in Green and Sustainable Chemistry*, *30*, 100482.

Reid, D. A., & Webster, J. (2007). Introduction to Fungi. *Kew Bulletin*.

Renfrew, M., Wittcoff, H., Floyd, D., & Glaser, D. (1954). Coatings of Olyamide and Epoxy Resin Blends. *Industrial & Engineering Chemistry*, *46*(11), 63–63.

RFA. (2017). Ethanol Co-products. *Renewable Fuels Association*.

Sailer, M. F. (2022). *Xylho Biofinish*.

Sailer, Michael F., van Nieuwenhuijzen, E. J., & Knol, W. (2010). Forming of a functional biofilm on wood surfaces. *Ecological Engineering*, *36*(2), 163–167.

Samyn, P., Schoukens, G., Stanssens, D., Vonck, L., & Van Den Abbeele, H. (n.d.). *Hydrophobic waterborne coating for cellulose containing hybrid organic nanoparticle pigments with vegetable oils*.

Schaak, D. D., & Lucht, M. J. (2016). *Biofilm treatment of composite materials containing mycelium*. Google Patents. https://patents.google.com/patent/US9469838B2/en

Sen, H. K., & Venugopalan, M. (1948). *Practical applications of recent lac research*.

Sharma, K. (2016). Lac insect-host plant interaction: Implications on quantity and quality of lac. *Beneficial Insect Farming-Benefits and Livelihood Generation*, 104.

Sharma, K. K. (2015). *Lac Insect Life Cycle , Lac Crop Cycle and Natural Resins and Gums Related Terminology*. *834010*(December), 6–13.

Sharma, K. K. (2017). Lac insects and host plants. *Industrial Entomology*, 157–180.

Sharma, K. K., Chowdhury, A. R., & Srivastava, S. (2020). Chemistry and applications of lac and its by-product. *Natural Materials and Products from Insects: Chemistry and Applications*, 21–37.

Shimizu, M., Saito, T., & Isogai, A. (2016). Water-resistant and high oxygen-barrier nanocellulose films with interfibrillar cross-linkages formed through multivalent metal ions. *Journal of Membrane Science*, *500*, 1–7.

Sietsma, J. H., & Wessels, J. G. H. (1979). Evidence for covalent linkages between chitin and β-glucan in a fungal wall. *Journal of General Microbiology*, *114*(1), 99–108.

Sietsma, J. H., & Wessels, J. G. H. (1981). Solubility of (1→3)-β-D/-(1→6)-β-D-glucan in fungal walls: Importance of presumed linkage between glucan and chitin. *Journal of General Microbiology*, *125*(1), 209–212.

Silva, F. A. G. S., Dourado, F., Gama, M., & Poças, F. (2020). *Nanocellulose Bio-Based Composites for Food Packaging*.

Spence, K. L., Venditti, R. A., Rojas, O. J., Pawlak, J. J., & Hubbe, M. A. (2011). Water Vapor Barrier Properties of Microfibrillated Cellulose Films. *BioResources*, *6*(4), 4370–4388.

Stemmelen, M., Lapinte, V., Habas, J. P., & Robin, J. J. (2015). Plant oil-based epoxy resins from fatty diamines and epoxidized vegetable oil. *European Polymer Journal*, *68*, 536–545.

Thakur, S., Misra, M., & Mohanty, A. K. (2019). Sustainable Hydrophobic and Moisture-Resistant Coating Derived from Downstream Corn Oil. *ACS Sustainable Chemistry and Engineering*, *7*(9), 8766–8774.

The Allen Consulting Group. (2009). National Waste Policy: Regulatory Impact Statement. *Policy*, *October*.

Thoemen, H., & Humphrey, P. E. (2005). Modeling the physical processes relevant during hot pressing of wood-based composites. Part I. Heat and mass transfer. *Holz Als Roh- Und Werkstoff 2005 64:1*, *64*(1), 1–10.

Thombare, N., Kumar, S., Kumari, U., Sakare, P., Yogi, R. K., Prasad, N., & Sharma, K. K. (2022). Shellac as a multifunctional biopolymer: A review on properties, applications and future potential. *International Journal of Biological Macromolecules*, *215*, 203–223.

Thomson, D. D., Wehmeier, S., Byfield, F. J., Janmey, P. A., Caballero-Lima, D., Crossley, A., & Brand, A. C. (2015). Contact-induced apical asymmetry drives the thigmotropic responses of Candida albicans hyphae. *Cellular Microbiology*.

van Nieuwenhuijzen, E. J., Sailer, M. F., van den Heuvel, E. R., Rensink, S., Adan, O. C. G., & Samson, R. A. (2018). Vegetable oils as carbon and energy source for Aureobasidium melanogenum in batch cultivation. *MicrobiologyOpen*, *October*, 1–12.

Vandelook, S., Elsacker, E., Van Wylick, A., De Laet, L., & Peeters, E. (2021). Current state and future prospects of pure mycelium materials. *Fungal Biology and Biotechnology*, *8*(1), 1–10.

Vasquez, E. S. L., & Vega, K. (2019). *Myco-accessories: Sustainable Wearables with Biodegradable Materials*.

Vega, K., & Kalkum, M. (2012). Chitin, chitinase responses, and invasive fungal infections. In *International Journal of Microbiology*.

Williams, R. S., & Feist, W. C. (1999). *Water Repellents and Water-repellent Preservatives for Wood*.

Xing, Y., Brewer, M., El-Gharabawy, H., Griffith, G., & Jones, P. (2018). Growing and testing mycelium bricks as building insulation materials. *IOP Conference Series: Earth and Environmental Science*, *121*(2).

Yuan, Y., He, N., Xue, Q., Guo, Q., Dong, L., Haruna, M. H., Zhang, X., Li, B., & Li, L. (2021). Shellac: A promising natural polymer in the food industry. *Trends in Food Science & Technology*, *109*, 139–153.

Zhao, H., Huang, L., Xiao, C. L., Liu, J., Wei, J., & Gao, X. (2010). Influence of culture media and environmental factors on mycelial growth and conidial production of Diplocarpon mali. *Letters in Applied Microbiology*, *50*(6), 639–644.