Journal of Sustainability Science and Management
Volume 17 Number 1, January 2022: 271-280
eISSN: 2672-7226

MYCELIUM-BASED COMPOSITE: A WAY FORWARD FOR RENEWABLE MATERIAL

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Submitted final draft: 16 April 2021 *Accepted: 26 April 2021* http://doi.org/10.46754/jssm.2022.01.018

Abstract: The fluctuation of petroleum prices, fast depletion of fossil resources and environmental problems are caused by polymer derived from petroleum or natural gas due to its non-renewable and non-biodegradable properties. Recently, the industry has emphasised designing sustainable biocomposite using eco-friendly, renewable, biodegradable and low energy consumption during the manufacturing process. This target can be obtained by producing a mycelium-based composite that uses the fungal mycelium matrix to bind composite material. Agricultural waste such as lignocellulosic biomass has a great potential to be converted into the mycelium-based composite. Fungal mycelia act as a natural adhesive or binder that binds together all particles of lignocellulosic biomass during fungal colonisation. The mycelium growing phenomenon is manipulated to produce the mycelium-based composite. Therefore, the selection of suitable fungi and type of lignocellulosic biomass is essential for good mycelial network development. This will pave the way for the mycelium-based composite from lignocellulosic biomass for its use in various applications.

Keywords: Mycelium-based composite, mycocomposite, binder, fungal mycelium, lignocellulosic biomass.

Introduction

The current trend for a sustainable and green economy proposes the development of bio-based material from renewable resources in product design and processes. Biocomposite formed by the combination of the matrix and natural fibre from wood or non-wood plant material. Most commonly resin used in biocomposite is originated from petroleum-based material such as polypropylene and polyethylene. These resin petroleum-based material are non-renewable, non-biodegradable and, most importantly, it is not sustainable for future use. Mycelium-based composite (MBC) is a biomaterial that is slowly gaining attention worldwide due to its benefits. This renewable MBC offers various advantages including low energy production process, low cost, biodegradable, recyclable and sustainable raw material (Jiang *et al.*, 2017). Mycelium-based composite results from the growth of filamentous fungi on agricultural wastes specifically lignocellulosic biomass. For instance, low-grade agricultural and forestry residues are often suitable for the manufacturing of foam-like mycelium composite (Jones *et al.*, 2019). Mycelium binds the lignocellulosic biomass by hyphal microfilaments in natural biological process to manufacture both low-value materials such as biofoam, packaging materials and higher value composite materials (Islam *et al.,* 2017). Renewable MBC is a key alternative for non-renewable packaging materials (Appels *et al.,* 2019).

Along these lines, the MBC serves several advantages as it does not require complex and high-end manufacturing processes, low energy consumption during production, low density, competitive strength, tensile and impact mechanical properties (Jiang *et al.,* 2013). It also has excellent resistance to corrosion and the possibility of being a sustainable source for a long period. Various utilisable substrates coupled with controlled processing techniques (e.g., growth environment and hot pressing) enable mycelium-derived materials to meet specific structural and functional requirements (Jones *et al.,* 2017; Haneef *et al.,* 2017). Mycelium-based materials have been manufactured for a diverse range of applications including paper, textiles, foams for packaging material, vehicle parts and electronics packaging materials, with the number of patents lodged indicative of application feasibility (Jones *et al.,* 2017).

Fungus is a microorganism that is able to colonise the substrates or biomass by utilising wide filamentous branch called hyphae. The fungal mycelium forms a three-dimensional network by growing at the tip and by branching out across the substrate. Secretion of enzymes by mycelium breaks down lignocellulosic biomass as a carbon source resulting in organic materials being degraded in time. After the completed colonisation of the biomass, the fungal growth could be stopped by drying and/or heating the material to form targeted MBC (Appels *et al.,* 2019). Tudryn *et al.* (2017) described the overall production of MBC, where the process begins with sterilisation of biomass followed by incubation with selected fungi, homogenisation and application into a pre-shaped mould.

White-rot fungi have high possibilities of producing mycelium-based composite due to their ability to secrete lignin-degrading enzymes that can degrade lignocellulosic biomass for nutrients uptake (Madadi & Abbas, 2017). Lignocellulosic biomass comprised lignin, cellulose and hemicellulose in which these structures become the nutrient or substrate for fungal growth once degraded. This is because the enzymes secreted by fungi degrade the lignin and consume cellulose as a carbon source and simultaneously forming an interwoven filamentous structure that penetrates the feeding substrate. Laccase (Lac), manganese peroxidase (MnP) and lignin peroxidase (LiP) are three common ligninolytic enzymes secreted by white-rot fungi for depolymerisation of lignocellulosic materials (Ellouze & Sayadi, 2016). *Ganoderma lucidum, Trametes versicolor* and *Pleurotus ostreatus* of Basidiomycota phylum are the three species of white-rot fungi commonly used in the manufacturing of mycelium-based composite (Attias *et al.,* 2017).

The aim of this review is to provide a brief insight into MBC production including fungal species used, properties of MBC and application as sustainable and renewable materials for future use.

Production of Mycelium-based Composite (MBC)

Mycelium-based composite (MBC) is defined as a composite formed using a natural fungal growth process that binds the lignocellulosic material into three-dimensional geometries (Figure 1), mirroring the mould shape that the substrate is packed into (Jones *et al.,* 2017; Holt *et al.,* 2012). MBC produced from different types of fungi determines the texture and mechanical properties of the end products of MBC depending on its applications.

In the process of MBC formation, the mycelium (vegetative part of a fungus consisting a mass of branching, thread-like hyphae) grows on lignocellulosic biomass and binds the

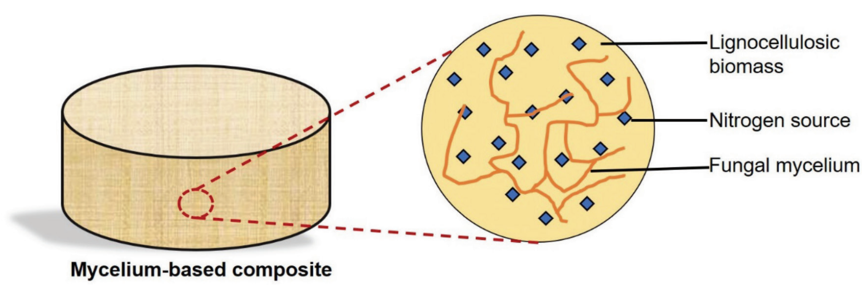

Figure 1: Diagram of basic components in mycelium-based composite

substrate tightly during fungal colonisation by secretion of ligninolytic enzymes. Apples *et al.* (2019) claimed that this mycelium secretes lignin-degrading enzymes such as laccase and peroxidase that convert polymers in the substrate into breakdown products that can be consumed as nutrients. Attias *et al.* (2019) claimed that fungal mycelia have the ability to bind and digest lignin and cellulose fibres of plants where it provides an inherent bonding, forming a natural, lightweight bio-composite, in which the fungal mycelium functions as the matrix and holds the substrate pieces together. The colonisation of fungus on a substrate is commonly stopped by drying and/or heating the materials. This method preserves fungus in hibernate state where fungal growth could be retrieved when moisture conditions become favourable again. Drying and/or heating of the substrate at certain time and stage during colonisation result in MBC (Appels *et al.,* 2019).

Figure 2 shows the general steps in overall process flow of MBC production described by Ghazvinian *et al.* (2019). Firstly, sterilisation of substrate will enable the mycelium to grow by autoclaving for 45 minutes at 121°C to prevent contamination with other microorganisms that exist on the substrate. Next, inoculation of fungus onto the sterilised substrate is carried out, followed by homogenisation at 25°C for 14 days. The fungus grows on a pre-shaped mould for three days at 25°C until mycelium completely binds the substrate particles together, resulting in a three-dimensional mesh of a live composite. Overall, a complete duration for the formation of MBC in total is 17 days. After colonisation, oven-drying at 90°C for 90 minutes is performed to kill the fungus and to evaporate the water, thus producing a stiff and foam-like mycelium-based material. The final product undergoes further analysis to study the general characteristics of mycelium composite such as morphological analysis, density measurements, mechanical tests (tensile and flexural strength test, elastic modulus etc), moisture exposure, water absorption and thermogravimetric analysis (Appels *et al.,* 2019).

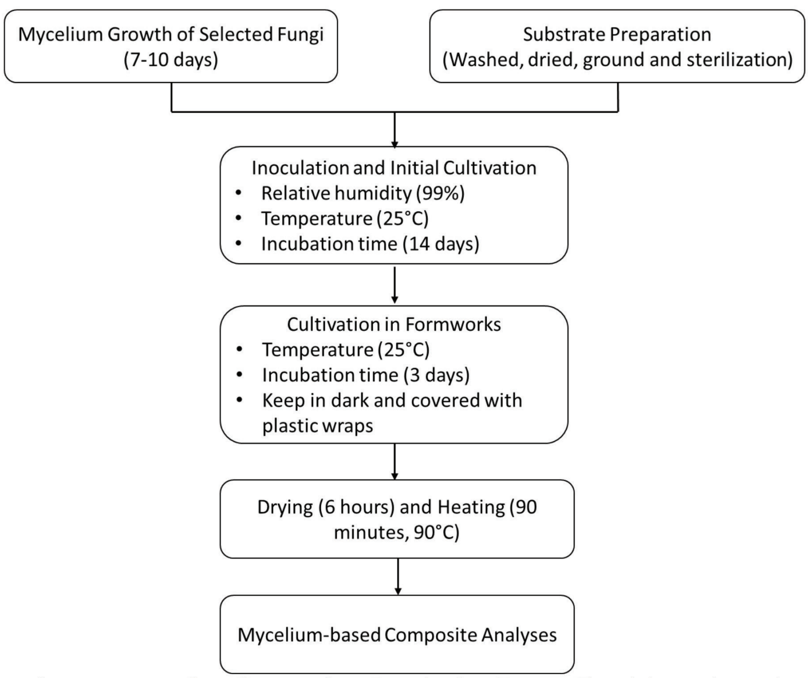

Figure 2: Process flow diagram of MBC production (Source: Ghazvinian *et al.*, 2019)

Fungal Species used in Production of MBC

Attias *et al.* (2019) claimed that selected fungal species has a significant influence on mycelium colonisation and the physico-mechanical properties of the final biocomposite. They summarised based on existing literature, that until 2018, about nine fungal species were commonly used in MBC production, predominantly from white-rot fungal species. White-rot fungi capable of decomposing complex molecular structure of lignin, beginning with digestion of short-chain carbohydrate and starch, followed by more complex polysaccharides (Xu *et al.*, 2013). Fungal species of *Ganoderma lucidum*, *Pleurotus ostreatus* and *Trametes versicolor* were found to be the most common for MBC production (Liu *et al.,* 2019). Recent studies reported on the discovery of new fungal species that have potential for MBC production such as *Pycnoporus sanguineus*, *Pleurotus albidus* and *Lentinus velutinus* (Bruscato *et al.*, 2019).

Figure 3 summarised the main fungal species used for fabricating mycelial composites according to current literature (Attias *et al.,* 2019). All species detected in the literature review belong to the phylum of Basidiomycota, which is characterized by hyphae that can split or fuse on a nano-level, creates clamp connections for vegetative reproduction and nutrient transfer and penetrate cavities on a microscopic level. Versteeg-Buschmann (2016) discussed that only 24 fungal species were identified in the literature review out of more than thirty thousand basidiomycetes species present. Thus, there is a necessity to screen and discover more fungal species to be utilised in MBC production.

Fungal type plays a significant effect on production of MBC. Thickness of hyphae, branching trend, rate of colonisation and surface topography vary depending on the selected fungal species (Attias *et al.,* 2019). Table 1 summarised the MBC production by different types of fungi using different substrates. The factors such as type of fungus, its growth condition, type of substrate and post-processing method determine the properties of pure mycelium materials (Islam *et al.,* 2017; Haneef *et al.,* 2017). Different types of fungi produce various visual impression from colour, texture and mycelium coverage. Chemical changes also vary due to different enzymatic degradation capability of fungi hence affecting MBC production. Haneef *et al.* (2017) reported that their study discovered *Ganoderma lucidum* produced less stiff mycelium composite when grown on cellulose compared to *Pleurotus ostreatus* with stiffer mycelia composite. The slightest gene modification can affect the properties of the mycelium. Interestingly, genetically modified *Schizophyllum commune* strain in which the hydrophobin gene SC3 is inactivated has a 3-4-fold higher maximum tensile strength when

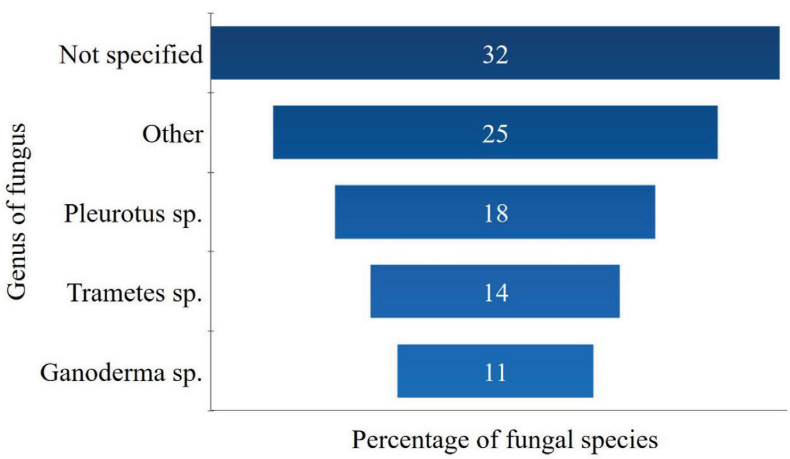

Figure 3: The main fungal species used for fabricating mycelium-based composites according to the current literature (Adopted from Attias *et al.,* 2019)

Table 1: Mycelium-based composite production by different types of fungi.

Fungus	Type of Substrate	Amount of Substrate	Humidity/Moisture Content	Reference
Pleurotus ostreatus	Sawdust Straw	5 kg	67.5 ± 2.5%	(Ghazvinian *et al.*, 2019)
Pleurotus albidus *Pycnoporus sanguineus* *Lentinus velutinus*	*Pinus* sp. wood	94% (w/w)	66%	(Bruscato *et al.*, 2019)
Pleurotus ostreatus *Trametes multicolor*	Beech sawdust Rapeseed straw Cotton	3 kg	65 - 70% (Beech sawdust, rapeseed straw) 55% (cotton fibre)	(Appels *et al.*, 2019)
Pleurotus ostreatus *Pleurotus eryngii* *Pycnoporus sanguineus*	Coconut powder-based	0.25 kg	60 - 70%	(Teixeira *et al.*, 2018)

compared to wild type (Appels *et al.,* 2019). This is caused by the increase in mycelium density of genetically modified fungi. Appels *et al.* (2019) reported in their study that composite formation from *Trametes multicolour* has the weakest compression strength compared to composite form by *Ganoderma sessile*.

Mechanical and Thermal Properties of MBC

The mechanical performance of mycelial composite is often related to mycelium constituent and mycelial network (Travaglini *et al.,* 2014; Jiang *et al.,* 2017). The numeric values for mechanical and thermal properties of MBC based on available literature are reported in Table 2. The latest study on chitin-glucan extract derived from mycelium shows that mycelium binder is strong (tensile strengths up to 25 MPa and fruiting body extract up to 200 MPa (Nawawi *et al.,* 2019). Limited mechanical performance is primarily contributed by insufficient fungal growth density to hold the substrate (Jones *et al.,* 2019). The growth of fungal on substrate varies significantly by species and substrate, affecting mechanical properties of materials (Jones *et al.,* 2019). On the other hand, the mechanical property of MBC often depends on the substrate in which the fungus colonised. To maximise tensile strength, the substrate must be rich in nutrient rather than strong to establish a dense mycelium network. Flexural property is measured when mycelium composite is subjected to bending experience; maximum tensile stress at one surface, to zero at the midplane, to maximum compressive stress at the opposite surface. Tudryn *et al.* (2017) discovered that increment of nutrition at homogenisation increased specific flexural stress and specific flexural modulus, due to porosity of the substrate, composite itself and degree of substrate degradation. Hot and cold pressing help to improve mechanical properties because it the porosity of the material and increases the material density in general (Appels *et al.,* 2019).

Mycelium by itself has no notable or useful fire-retardant properties. Degradation and thermal stability of mycelia alone are equal to other typical cellulosic and biological derived materials (Yang *et al.,* 2007). However, MBC made up of substrates that are rich in natural phenolic polymers, such as lignin, and naturally occurring or synthetically produced silica (SiO2) can exhibit significantly improved thermal degradation, fire reaction and safety properties (Jones *et al.,* 2019). Their study also demonstrated that MBC containing large quantities of rice hulls (75 wt%) have lower average and peak heat release rates (107 kW/m^2 and 185 kW/m^2, respectively) compared to synthetic foams, such as extruded polystyrene insulation foam (XPS, 114 kW/m^2 and 503 kW/m^2, respectively). One way to further improve the thermal stability of MBC is by the addition of glass fines within the substrate of the composite. This is because glass fines significantly increase the inflammable content of the material.

Table 2: Mechanical and thermal properties of MBC from literature (Source: Appels *et al.,* 2019; Holt *et al.,* 2012)

Property	Value
Density (g/cm^3)	0.10 – 0.39
Tensile strength (MPa)	0.01 – 0.24
Elastic modulus (MPa)	2 – 97
Flexural strength (MPa)	0.05 – 0.87
Flexural modulus (MPa)	1 – 80
Compressive strength (kPa)	1 – 72
Thermal conductivity (W $m^{-1}K^{-1}$)	0.10 – 0.18

Applications of MBC

Over the years, the applications of MBC products are broadening into various fields and usages. Mycelium materials have been manufactured for a diverse range of applications (Jones *et al.,* 2017). Ecovative Design LLC (Ecovative) is a leading-edge biocomposite materials firm that employs the mushroom kingdom in an array of products, most of which supersede common uses of polystyrene and aldehydes.

Currently, Ecovative produces protective packaging materials that are environmentally responsible, with an equal performance of polystyrene foam at a similar cost. These mycelium foam packaging products were commercialised under trademarked EcoCradle® that is used by Dell Inc., Steelcase Inc., Crate and Barrel and Sealed Air. Dell Inc. used the protective packaging for the computer while Sealed Air covered their wine bottle using the mycelium foam packaging. Table 3 shows the application and products of mycocomposite material in industries. The advantages of mycelium foam packaging biodegradable composites are environmentally friendly, sustainable for a long period, low cost of disposal and low manufacturing cost.

MBC is also used as building materials that act as insulator such as structural insulating panels (SIPs) and acoustical tiles. In the automotive industry, Ecovative's biocomposite can replace polypropylene foams commonly used in cars. Specially tuned mycomaterials can replace synthetic foams found in bumpers, doors, roofs, engine bays, trunk liners, dashboards and seats. The materials able to absorb impact, insulate, dampen sound, and provide a lightweight structure within an automobile. Meanwhile, for home and garden applications, they are used as containers, garden planters, wine shippers and candle holders.

This biocomposite is also widely used as construction brick for architecture structure since 2009 when *Ganoderma lucidum* and sawdust were used to produce 500 bricks called 'Mycotectural Alpha' teahouse which was displayed during 'Eat Art' Exhibition (Ross, 2014). In 2014, Young Architects Program was held in the New York Museum of Modern Art's and a 12-metre height mycelium structure was produced and displayed during the competition. It was named the Hy-Fi organic compostable tower and won the competition. It was made up of more than 10000 bricks produced from shredded corn stalks and undisclosed fungal species (Rajagopal, 2014).

Table 3: Application and products of commercialised mycelium-based composite materials in industries (Source: Gurunathan *et al.,* 2015; Jones *et al.,* 2017; Ecovative design, 2019)

Product/Commercial Name	**Application**
Construction industry	• Construction materials to build 'Hy-Fi' organic compostable tower and Mycotectural Alpha' teahouse • Wood substitutes such as laminates, panels, partitions, door frames, shutters, and roofing in construction 
Skin care industry	Skin care product (Make-up sponge)/ Mycoflex™ 
Automotive industry	Use in car seats, dashboard coverings, roofs and trunk lids by car manufacturers (Volkswagen, Ford, Honda and General Motors).
Packaging industry	Foam packaging/EcoCradle®: Protective packaging for shipping items such as computer and wine during shipping and transportation.  

The main advantages of mycocomposite materials made using natural fibres (e.g., kenaf, jute, hemp, flax, bamboo, and sisal) over traditional synthetic composites are low cost, low density, competitive strength, tensile and impact mechanical properties, reduced energy consumption, the potential for CO_2 sequestration if done at large scale, and perhaps most important of all, biodegradability. Below is the table of the benefits of mycocomposite materials compared to synthetic alternatives from Evocative Design LLC viewpoint (Table 4).

Future of Mycelium-Based Composite

For ages, petroleum-based products have been used for many applications in the packaging, cosmetic, automotive, textiles and construction industry. The growing concerns of society towards depleting resources of the petroleum as well as increasing awareness on the impact of non-recyclable and non-biodegradable materials on the ecological system have shifted the perceptions of the global society. Following this, more research has been performed to cater to the problems and offers more options to substitute petroleum-based products. In line with the transition towards biodegradable and sustainable materials, renewable mycelium-based materials seem to have high potential as an alternative as well as heavy reliance reduction onto petroleum-based products in the future.

Until recently, the increase of eco-conscious consumers in the new generation has urged multinational companies and local businesses to provide more eco-friendly products made from sustainable resources in the market. A report by Elsacker *et al.* (2019) stated the use of MBC as a substitute for fossil-based and synthetic materials such as polyurethane and polystyrene in the architecture and construction industry. The application of MBC for packaging and insulation has grown rapidly as a sustainable alternative for polystyrene (Abhijith *et al.*, 2018). The biodegradable characteristic of MBC has gained interest in the agricultural industry to reuse the MBC as a substrate for seedling production, soil conditioner and organic fertilizer (Teixeira *et al.,* 2018). As a new approach to recent technology, there are a lot more to explore particularly in the properties of the MBC that mainly depend on the types of fungus, substrate, growth conditions, additives and processing materials (Appels *et al.,* 2019). Moreover, there are still many aspects of challenges such as structure, function as well as stability of MBC during storage, use and disposal that need to be further studied. Nevertheless, the current application of MBC in various industries has proved that it has a high potential to suppress the use of petroleum-based products in future practices.

Table 4: Comparison between mycelium-based products and mainstream products in the market (Source: Zeller & Zocher, 2012)

Properties	Evocative Design Products	Comparable Mainstream Product
Product toxicity	Materials contain no toxic chemicals, emit no gases and completely inert.	Polystyrene made up of chemicals suspected by US government to be carcinogenic and emit toxic gases
Raw material toxicity	Primary raw materials consume organic agricultural waste, steam clean to remove contamination and mycelium is grown aseptically.	Polystyrene is composed of highly toxic materials like styrene and benzene and particleboard is made using formaldehyde adhesive.
Biodegradability	Finished product can be home composted when no longer needed.	Traditionally plastic materials never degrade, and proper recycling is required.
Sustainability	100% renewable	Production relies on non-renewable resources, burdened with economic and ecological constraint.

Conclusion

This brief review has highlighted MBC as a sustainable resource to substitute conventional materials. The outstanding advantages served by MBC such as sustainability and biodegradability are the key features for future green composites. Indeed, the properties of MBC as the final product is mainly dependent on fungal species selection. White-rot fungal species is the most commonly used in MBC production. The mechanical and thermal properties of MBC, however, need to be improved in an attempt to use MBC as a substituted material to synthetic composites. The utilisation of MBC in various applications has created a new opportunity for the industries and is a way forward to produce a sustainable biomaterial for future application of MBC.

Acknowledgements

The authors would like to thank the Ministry of Education of Malaysia (MOE) for supporting this study through Fundamental Research Grant Scheme (FRGS/1/2018/STG05/UPM/02/23).

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